

AD-A077 531

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL--ETC F/6 21/5  
AN ANALYSIS AND SYNTHESIS OF ENGINE CONDITION MONITORING SYSTEM--ETC(U)  
SEP 79 J W CHAPMAN, C L PAGE

UNCLASSIFIED

AFIT-LSSR-27-798

NL

1 OF 2  
AD  
A077531

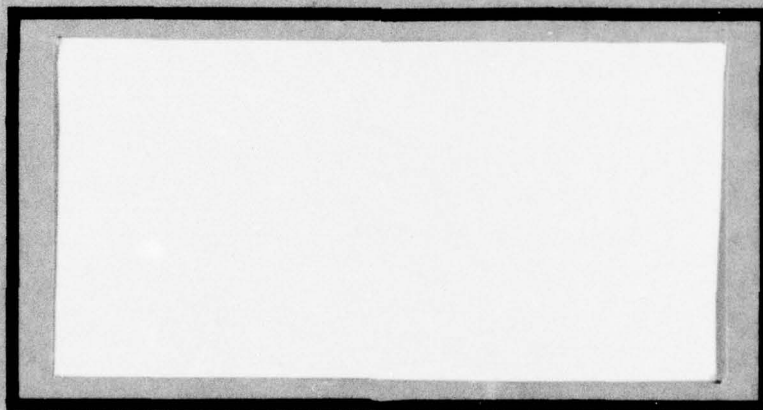


AD A 077531



3  
LEVEL

DDC  
RECEIVED  
DEC 4 1979  
A



DDC FILE COPY

UNITED STATES AIR FORCE  
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY  
Wright-Patterson Air Force Base, Ohio

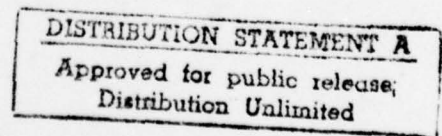
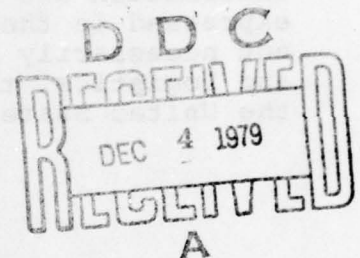
DISTRIBUTION STATEMENT A  
Approved for public release  
Distribution Unlimited

79 12 3 058

AN ANALYSIS AND SYNTHESIS  
OF ENGINE CONDITION  
MONITORING SYSTEMS

Jack W. Chapman, Jr., Captain, USAF  
Charles L. Page, Jr., Captain, USAF

LSSR 27-79B



The contents of the document are technically accurate, and no sensitive items, detrimental ideas, or deleterious information are contained therein. Furthermore, the views expressed in the document are those of the author(s) and do not necessarily reflect the views of the School of Systems and Logistics, the Air University, the Air Training Command, the United States Air Force, or the Department of Defense.

## AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to determine the potential for current and future applications of AFIT thesis research. Please return completed questionnaires to: AFIT/ LSH (Thesis Feedback), Wright-Patterson AFB, Ohio 45433.

1. Did this research contribute to a current Air Force project?

- a. Yes                      b. No

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not researched it?

- a. Yes                      b. No

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of man-power and/or dollars?

a. Man-years \_\_\_\_\_ \$ \_\_\_\_\_ (Contract).

b. Man-years \_\_\_\_\_ \$ \_\_\_\_\_ (In-house).

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3 above), what is your estimate of its significance?

- a. Highly                      b. Significant                      c. Slightly                      d. Of No  
Significant                      Significant                      Significance

5. Comments:

\_\_\_\_\_  
Name and Grade

\_\_\_\_\_  
Position

\_\_\_\_\_  
Organization

\_\_\_\_\_  
Location

OFFICIAL BUSINESS  
PENALTY FOR PRIVATE USE, \$300



NO POSTAGE  
NECESSARY  
IF MAILED  
IN THE  
UNITED STATES

**BUSINESS REPLY MAIL**

FIRST CLASS PERMIT NO. 73236 WASHINGTON D.C.

POSTAGE WILL BE PAID BY ADDRESSEE

AFIT/LSH (Thesis Feedback)  
Wright-Patterson AFB OH 45433



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SLSR 27-79B	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN ANALYSIS AND SYNTHESIS OF ENGINE CONDITION MONITORING SYSTEMS	5. TYPE OF REPORT & PERIOD COVERED Master's Thesis	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Jack W./Chapman, Jr., Captain, USAF Charles L./Page, Jr., Captain, USAF	8. CONTRACT OR GRANT NUMBER(s)	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
9. PERFORMING ORGANIZATION NAME AND ADDRESS Graduate Education Division School of Systems and Logistics Air Force Institute of Technology, WPAFB OH	11. CONTROLLING OFFICE NAME AND ADDRESS Department of Research and Administrative Management AFIT/LSGR, WPAFB OH 45433	12. REPORT DATE September 1979
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) AFIT-LSLR-27-79B	13. NUMBER OF PAGES 124	15. SECURITY CLASS. (of this report) 12138
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited  1 OCT 1979		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Engine condition monitoring Engine monitoring systems Engine management Reliability centered maintenance On condition maintenance		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Thesis Chairman: Leslie J. Zambo, Major, USAF		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

012 250

LB

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Engine condition monitoring systems have been developed to assist flight line maintenance activities and aid in the transition of aircraft engine maintenance philosophy from that of maximum operating time to reliability centered or on condition maintenance. This study includes a comprehensive review of past, current, and proposed Air Force applications of turbine engine monitoring systems to describe the major features of TEMS. Engine performance data output from TEMS to the various engine management functions are analyzed. The authors conclude that TEMS data and the existing or proposed engine management systems are not directly compatible. Moreover, the analysis indicates that implementation of TEMS and an on condition maintenance policy would require a greatly expanded data base to accomplish the required engine management record keeping, monitoring, and forecasting tasks. Several recommendations are offered for interfacing TEMS with the engine management systems. Areas for further research are suggested.

Accession	
NTIS	<input checked="checked" type="checkbox"/>
DDC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
A	

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

LSSR 27-79B

AN ANALYSIS AND SYNTHESIS  
OF ENGINE CONDITION  
MONITORING SYSTEMS

A Thesis

Presented to the Faculty of the School of Systems and Logistics  
of the Air Force Institute of Technology  
Air University

In Partial Fulfillment of the Requirements for the  
Degrees of Master of Science in Logistics Management

By

Jack W. Chapman, Jr., BA  
Captain, USAF

Charles L. Page, Jr., BS  
Captain, USAF

September 1979

Approved for public release; distribution unlimited

This thesis, written by

Captain Jack W. Chapman, Jr.

and

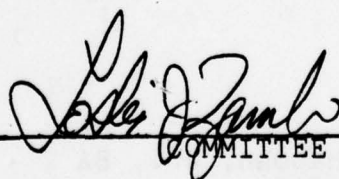
Captain Charles L. Page, Jr.

has been accepted by the undersigned on behalf of the faculty  
of the School of Systems and Logistics in partial fulfillment  
of the requirements for the degrees of

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT  
(Captain Jack W. Chapman, Jr.)

MASTER OF SCIENCE IN LOGISTICS MANAGEMENT  
(INTERNATIONAL LOGISTICS MANAGEMENT MAJOR)  
(Captain Charles L. Page, Jr.)

DATE: 7 September 1979

  
COMMITTEE CHAIRMAN

## ACKNOWLEDGEMENTS

The authors wish to express their sincere appreciation to those people whose assistance was vital to the completion of this study. Without the advice, assistance, and information provided by Dr. Ben Williams and Captain William Rutley, this study could not have come to fruition. The continuing patience and encouragement by our thesis chairman, Major Leslie Zambo, gave us the motivation to complete this effort. The superb typing skill and timely return of draft and final copies by Mrs. Peggy Upton was of inestimable value in the completion of the final manuscript.

The contribution of these individuals provided the support without which this work would have been impossible. However, the content and validity of the analysis, conclusions, and recommendations are solely the responsibility of the authors.

## TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS . . . . .	iii
TABLE OF CONTENTS . . . . .	iv
LIST OF TABLES . . . . .	vii
LIST OF FIGURES. . . . .	viii
 Chapter	
I. INTRODUCTION . . . . .	1
Overview . . . . .	1
Statement of the Problem . . . . .	3
Objectives . . . . .	4
Research Questions . . . . .	5
Methodology. . . . .	5
Sources . . . . .	5
Scope . . . . .	7
Plan of Presentation . . . . .	8
II. LITERATURE REVIEW. . . . .	9
Introduction . . . . .	9
Engine Management System . . . . .	11
Background . . . . .	11
Management Levels. . . . .	11
Tasks . . . . .	15

Data Systems . . . . .	17
Comprehensive Engine Management System (CEMS) . . . . .	22
Reliability Centered Maintenance/ On Condition Maintenance . . . . .	28
Reliability Centered Maintenance Program (RCMP) . . . . .	31
On Condition Maintenance . . . . .	33
Engine Condition Monitoring. . . . .	35
Objectives . . . . .	35
Concepts . . . . .	39
Major Impacts on Engine Reliability . .	43
Potential Benefits . . . . .	47
III. ANALYSIS OF AIR FORCE TEMS APPLICATIONS. .	56
Synopsis . . . . .	56
Background Descriptions. . . . .	56
Comparisons. . . . .	63
Trends . . . . .	68
Synthesis. . . . .	69
IV. TEMS INTERFACE WITH ENGINE MANAGEMENT . . .	76
Introduction . . . . .	76
TEMS Output . . . . .	77
RCM/OCM Interface Considerations . . . . .	82
Interfaces with Engine Management. . . . .	84
Current Maintenance Interface . . . . .	84
Current TEMS Interfaces. . . . .	86
Projected TEMS-CEMS Interface. . . . .	86
Recorded Keeping Task . . . . .	86

Monitoring Task . . . . .	93
Forecasting Task. . . . .	93
V. CONCLUSIONS AND RECOMMENDATIONS . . . . .	98
Summary . . . . .	98
Conclusions . . . . .	98
Research Question One . . . . .	98
Research Question Two . . . . .	99
Research Question Three . . . . .	100
Research Question Four. . . . .	100
Recommendations . . . . .	101
Recommendation for Further Research . . . . .	104
APPENDIX . . . . .	106
GLOSSARY. . . . .	107
SELECTED BIBLIOGRAPHY . . . . .	116
A. REFERENCES CITED. . . . .	117
B. RELATED SOURCES . . . . .	121

## LIST OF TABLES

Table		Page
1.	Actuarial Failure Factors	18
2.	Engine Parameter Categories	71
3.	Parameter Use Categories	72

## LIST OF FIGURES

Figure		Page
1	Engine Flow Cycle	12
2	AF Form 1534, Engine Status Report	19
3	CEMS Data Interfaces	25
4	CEMS Implementation Increments	27
5	Effects of MOT Concept	30
6	TEMS Conceptual Model	65
7	Synthesis of TEMS Output	74
8	Example T-38 EHMS Raw Data Output	79
9	Example T-38 EHMS Event and Diagnostic Outputs	80
10	Example T-38 EHMS Trented Raw Data	81
11	Current Maintenance - Engine Manage- ment Information Interface	85
12	Current TEMS Interface (Added)	87
13	Envisioned TEMS-CEMS Interface (Added)	88
14	Conceptual Model of Current Engine Management Record Matrix	91
15	Possible CEMS Record Matrix Under RCM/OCM Concept	92
16	Example Engine Failure Rate Table	95
17	Current Forecasting Model	96
18	Possible Future Forecast Model	97
19	Recommended TEMS Interface	103

## CHAPTER I

### INTRODUCTION

#### OVERVIEW

The design, development, operation, and maintenance of technologically superior weapons systems is vital to maintaining a viable defense posture in the face of the numerical advantages of our opponents. The increasing complexity of the advanced aerospace weapons required to achieve this goal has necessitated the collateral development of improved support systems to maintain and increase availability of operational aircraft, increase sortie rates, and reduce logistic support costs. To meet this objective the Department of Defense has charted the path of its aircraft maintenance efforts in the direction of "Reliability Centered" or "On Condition" maintenance (38:III-41; 44:B-16). Under this concept maintenance tasks are performed "as required" versus "time-phased" or "maximum operating time" schedules. Key to implementation of this concept is the development of systems and procedures to provide accurate and timely indications of needed maintenance (37).

Of the numerous major aircraft subsystems, it has been documented that the engine is not only a major

contributor to maintenance requirements and support costs, but, more importantly, a major contributor to aircraft "not-mission capable" status (14:13-18,43-49). The US Air Force jet engine inventory exceeded 41,000 units in June 1978 with a total value of eight billion dollars. Moreover, approximately one billion dollars were spent on spare engines, spare engine parts, and engine maintenance during fiscal year 1978. This engine support cost has been estimated to reach fourteen billion dollars by FY84 with the addition of the F100 and TF34 engines for the F-15/F-16 and A-10 aircraft, respectively (4; 5). Thus a prime candidate for the application of on condition maintenance implementation technology has been the aircraft turbine engine.

The aircraft and engine manufacturers have developed several types of engine monitoring systems to provide the military services the capability to accomplish this significant change in aircraft engine maintenance philosophy. These systems, which the Air Force has labeled turbine engine monitoring systems (TEMS), were designed to measure, evaluate, and record various engine operating parameters, such as operating time/cycles, vibration, temperature, and pressures. Previous TEMS applications, as well as systems currently being developed and tested have used several different methodologies to provide the data required for determining engine condition/health and maintenance

requirements. System differences included parameter selection, data analysis, and data collection for interface with the maintenance and logistics data systems.

The Air Force Logistics Command (AFLC) has initiated the development of an automated data system to provide logistics managers with the information necessary to implement and support the reliability centered maintenance concept. The Comprehensive Engine Management System (CEMS) is planned to replace the current D024 engine management data system, which monitors serial numbered engines according to inventory, location, operational status, and total operating time criteria. TEMS is envisioned to be an integral portion of the total CEMS and is planned to provide more advanced engine management data and analysis through manual or automatically collected diagnostic data.

#### STATEMENT OF THE PROBLEM

The various engine monitoring concepts and the development of hardware to support these concepts have been service tested by the DOD and allied military services and the commercial airlines. The results of these tests, as well as information regarding proposed engine monitoring systems, required review and synthesis to provide a consolidated presentation of the literature concerning these efforts. Specifically, the similarities and differences

between these engine monitoring systems should be described and compared to identify any trends in system development or application. Moreover, the respective system approaches to integration with the Air Force engine logistics management systems should be examined to ascertain their future compatibility with the Comprehensive Engine Management System.

### OBJECTIVES

There were three objectives to this study:

1. Provide a synopsis of the major features of past, present, and proposed engine monitoring systems based on a systematic and comprehensive review of the existing literature.
2. Describe and compare the similarities and differences between the systems reviewed. This comparison should enable the determination and identification of trends in engine monitoring system development and applications.
3. Identify the potential for interface between the Air Force engine monitoring systems reviewed and the Air Force engine logistics management systems.

## RESEARCH QUESTIONS

To guide the research the following specific questions were developed:

1. What are the major features of past, current, and proposed Air Force TEMS applications?
2. What are the differences and similarities between the reviewed systems, including engine operating parameters monitored and methods of data collection and analysis?
3. Are there any trends in engine monitoring system development in terms of the identified similarities and differences?
4. How does/can TEMS interface with current and proposed Air Force engine management systems?

## METHODOLOGY

This section outlines the procedures used to gather and analyze the information necessary to address the research questions posed in the previous section. Specifically, the sources of this information are reviewed, the scope of the overall research effort is defined, and the plan of presentation is outlined.

### Sources

Since engine condition monitoring is a contemporary issue, a major source of documentation was the current

files of the engine management functions of the Air Force Logistics Command (AFLC) and the Aeronautical Systems Division (ASD) located at Wright-Patterson AFB OH. These documents consisted primarily of reports, briefings, and letters concerning TEMS status and on condition maintenance concepts. Air Force Regulations, Manuals, Technical Orders, and Department of Defense Directives were reviewed to provide background information on maintenance and engine management policy and procedures. Status reports and TEMS manufacturers' hardware demonstration reports provided descriptions of the various TEMS applications. Library research through the Defense Documentation Center and the Defense Logistics Studies Information Exchange produced several reports and studies pertaining to engine condition monitoring concepts and benefits. Personal interviews were conducted with AFLC and ASD personnel to obtain current TEMS information. Additionally, telephone interviews were conducted with Tactical Air Command, Langley AFB VA, and San Antonio Air Logistics Center, Kelly AFB TX, personnel involved in TEMS program management and development.

These personal and telephone interviews were not formally structured and were conducted without a specific list of questions. This unstructured format promoted a more candid atmosphere during the interview. This method was preferred in this research as it allowed for immediate feedback, continued questioning about a specific area,

and a maximum flow of information. In addition to permitting return visits, immediate clarification of any ambiguities was sought and amplification was requested for areas of critical interest. Personnel interviewed are referenced in the text where appropriate and in the bibliography.

These sources were used to provide the basis for the literature review, system descriptions, and TEMS synthesis presented in subsequent chapters.

### Scope

Turbine engine monitoring includes historical record keeping in its broadest sense. This study addressed only those specific programs and hardware that incorporated manual or automatic acquisition of engine performance data, selective or continuous data storage, and subsequent manual or computer processing and trending of this data to affect maintenance, logistics, and operational decisions. Programs which were based on statistical or periodic inspection or maintenance intervals were excluded from the system descriptions. Moreover, other engine performance diagnostic methods such as oil analysis and radiographics were addressed only as they related to the conceptual basis of overall engine monitoring. The primary emphasis was on Air Force TEMS applications and concepts; however, other DOD and allied service TEMS programs as well as commercial airline applications were reviewed to aid in the explanation of engine monitoring concepts.

## Plan of Presentation

The study is presented in four chapters. Chapter II is devoted to a review of engine management functions and engine monitoring concepts and potential benefits. The reliability centered maintenance and on condition maintenance concepts are examined. Chapter III consists of descriptions of selected TEMS applications. A synthesis of these applications is developed and apparent trends in TEMS development and implementation are identified. Chapter IV presents an analysis of the TEMS interface with the existing engine management system. The proposed on condition maintenance concept is also reviewed in conjunction with the potential TEMS interface. Chapter V presents the research conclusions and recommendations.

## CHAPTER II

### LITERATURE REVIEW

#### INTRODUCTION

Over the past fifteen years, the commercial airline industry, the military services, and several technical/professional organizations, such as the AF Aero Propulsion Laboratory and the Society of Automotive Engineers, have created a sizeable literature base regarding engine monitoring systems. These studies have ranged from theoretical and conceptual research on engine performance monitoring and failure prediction methodology to the analysis of results from service tests on actual installations of such monitoring and diagnostic hardware. The major objective of these research efforts has been to develop and test the diagnostic techniques necessary to enable development and implementation of engine monitoring systems which have been considered necessary to improve engine operational availability, reduce engine support costs, and increase engine reliability and safety. These efforts have produced only limited and somewhat controversial results and none have led to validated maintenance or logistics costs savings (14:7). The purpose of this study was to present a synthesis of these programs,

with primary emphasis on Air Force projects, and to examine the interface between TEMS and the AF engine management system.

As the primary objective of engine diagnostics has been to facilitate the implementation of on condition engine maintenance, the diagnostic system should be thoroughly integrated into the overall logistics maintenance management system. This is necessary to realize fully the potential reductions in operational support cost. The interface between the diagnostic system data and the management system using this data is critical. This was examined in this research.

Various terms have been used throughout the literature to describe monitoring methodologies and related systems. The most prevalent of these terms have been engine diagnostics, engine health, engine condition, and engine monitoring. Regardless of this differing terminology, the basic underlying purpose of all the systems or methods described in the literature has been to provide a near real-time assessment of the actual operating condition of the engine. The data gathered from this assessment have been intended to be used by maintenance and engine management functions, to aid in fault isolation, to develop trend analysis on engine operational characteristics, and to permit projections of engine or component failure or replacement. Consequently, the term Turbine Engine Monitoring System (TEMS), which

has been adopted by the Air Force to describe these engine diagnostic efforts, was used throughout this study when referring to the generic concept.

## ENGINE MANAGEMENT SYSTEM

### Background

The US Air Force engine management system was designed to control and monitor the flow of Air Force aircraft propulsion units through the engine flow cycle depicted in Figure 1 (9:p.1-2). This process, which has been the responsibility of the Air Force Logistics Command, consists of three major tasks on three organizational levels and supports the three levels of engine maintenance (3:Ch.4; 43:Ch.3).

### Management Levels

The Air Force engine management system consists of three major levels. These are (1) base level, (2) depots, and (3) command (2:Ch.11; 3:Ch.4; 43:Ch.3,Ch.11).

At the base level the Base Engine Manager (EM) monitors the inventory and movement of all engines located at that base and ensures accurate and timely submission of engine status change reports. This level also conducts the first two levels of engine maintenance production consisting of flight line and jet engine intermediate maintenance

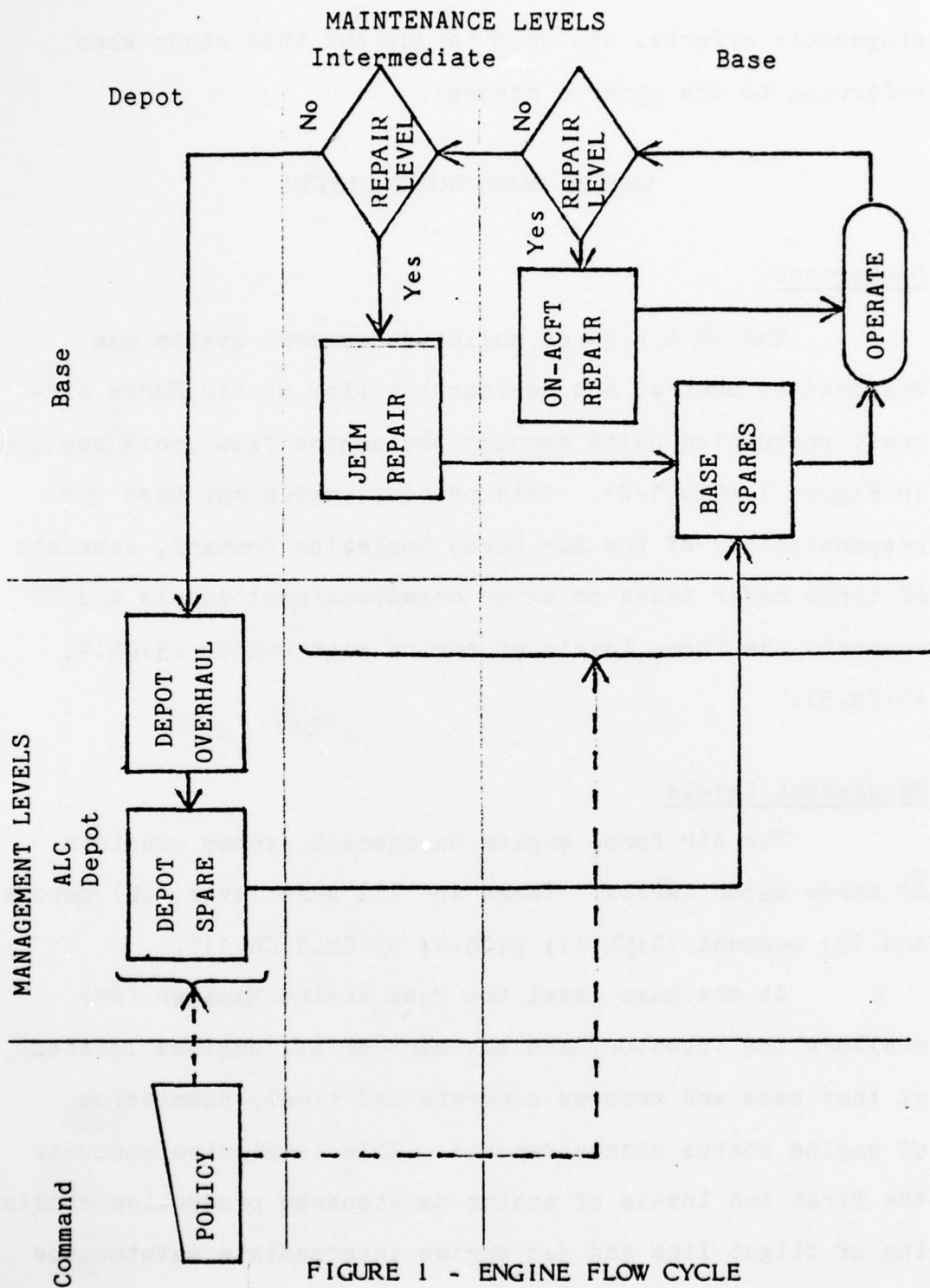


FIGURE 1 - ENGINE FLOW CYCLE

(JEIM). Flight line engine maintenance involves the troubleshooting, and the repair of discrepancies which can or should be performed while the engine is installed on the aircraft. The transition from flight line maintenance to JEIM has been predicated upon the identification of scheduled or unscheduled maintenance tasks which require engine removal (23; 31; 37). Factors which indicate removal of the engine have included estimated repair time, capability to repair the failure while the engine is installed and ability to accurately identify the failure. JEIM may be conducted locally or at a Queen Bee centralized repair facility. The transition from JEIM to depot level maintenance has been determined by several factors including criticality of the base engine stock level, cost of repair versus hours remaining before maximum operating time, possibility of discrepancies undetectable at base level, and failure of base level maintenance to correct discrepancies (43:p.11-2).

The Air Logistics Center (ALC) is the second major management level. The Air Force Logistics Command operates two engine depots for major repair (Oklahoma City and San Antonio ALCs). These ALCs perform depot maintenance, which is the third level of maintenance, on engines for which they have been assigned as Technology Repair Centers (TRC). An Engine Item Manager (EIM) monitors each engine type with overall responsibility for engine management. EIMs

process and use the historical data to forecast failures and scheduled removals over a two year period to predict workloads, spare parts procurement, and to calculate stock-age objectives for both depot and base levels (43:p.3-1).

The third level of the engine management structure is Headquarters Air Force Logistics Command. They have been responsible for integrating logistics support for the engine fleet over the equipment life cycle. AFLC logisticians have been concerned with monitoring performance, reliability, and maintainability. They have been responsible for establishing policy for inventory control, maintenance procedures, and developing the software used throughout the Air Force to perform logistical analysis and support (43:p.3-1).

In addition to the line maintenance and logistics organizations, the operational commands provide a parallel management function. The major command engine managers (MAJCOM EM) have been concerned with monitoring fleet performance. They have required a high degree of visibility into engine health for determination of the mission performance capability and the readiness posture of each base and the overall command fleet. Ideally, engine problems and fleetwide trends should be identified and corrected before substantial degradation in availability and readiness can occur. Like their counterparts at the ALCs, MAJCOM

EMs also predict workloads, determine spare engine requirements, and calculated stockage objectives (43:p.3-2).

### Tasks

The tasks of the AF engine management system were summarized into three major categories: record keeping, monitoring, and forecasting (3:Ch.4; 28:Section 2; 41:Ch.6; 43:Ch.4). The record keeping task had been accomplished through reports from the base level engine managers' (EM) updates of such factors as status (installed versus spare), condition (serviceable or unserviceable), location, configuration (modifications completed), engine operating time, account transfers (receipts or shipments), and maintenance category of each on-hand engine. Reports are transmitted to and processed by Oklahoma City ALC (OC-ALC), which has been responsible for maintaining and operating the D024, Propulsion Unit Logistics System, to update the central engine master file for each engine. The master records and transactions generated by these reports have been used in the monitoring and forecasting tasks.

The monitoring task is accomplished by reviews of system products in the form of listings and reports built from the inputs of the record keeping and forecasting tasks. The management analysis generally included the comparison of actual experience with forecasts or pre-established standards for areas such as base level engine

stockage objective, intermediate maintenance return to service rates, pipeline times, failure rates, and expected engine life. Such monitoring has been performed at each organizational level to varying degrees (43:Ch.4).

The computations performed in the forecasting task were the keys to the translation of the transactions and experience, gathered and retained during the record keeping task, into the engine management actions taken as a result of the forecasting and monitoring tasks. Determinations of spare engine requirements, and their dispersal to operating bases, inventory control, and maintenance workload forecasts have been all based on failure factors computed through the Air Force Actuarial System for Engines (43:p.1-1).

The actuarial method as used in this system has been defined as:

... applying the principles and techniques of actuarial science (especially studies in life contingencies) to the field of Air Force engine management (41:p.1-17).

This method is founded on two basic principles. First, just as with humans, "... the probability of death (or failure) is dependent on, or is a function of age (40:p.2-17.)" Second, the life span of an engine (or human) could be considered as a series of successive age intervals, which normally has been 20 operating hours for engines and one year for humans beginning at age zero (birth) through some

arbitrary maximum age where none will remain (death or, in the case of engines, maximum operating time) (40:p.2-1). Based on these two principles, failures occurring before maximum operating time have been related to the age interval of the failed engine and used to compute the failure factors (28; 41) listed in Table 1. These factors were then used in combination with various future program factors to produce engine spares requirements, stockage objective, and workload forecasts.

#### Data Systems

The engine maintenance and performance data generated through the base-level maintenance data collection system have been the primary source of information required to support the engine management functions at each level. The AF Form 1534, Engine Status Report (Figure 2), was the source document submitted by base engine managers to update the central engine master file maintained on the D024, Propulsion Unit Logistics System. The D024 had been segmented into several parts to provide specialized data system support to the various engine management functions, such as inventory management (D024K), status reporting (D024A), configuration management (D024I), and actuarial forecasts (D024K). This data system supported the engine management tasks and the central AF engine stock record account FJ2031 at OC-ALC (28: Section II; 42:Ch.1,Ch.9).

### Crude Failure Rates - Depot Maintenance

- Field Maintenance

### Smoothed Failure Rates - Depot Maintenance

- Field Maintenance

- Combined

### Engine Failure Rate Table - Depot Maintenance

- Field Maintenance

Field Maintenance Removal Interval (FMRI)

Overhaul Removal Interval (OHRI)

Combined Removal Interval (CMRI)

: Jet Engine Base Maintenance Return Rate (JEIM/RR)

Actuarial Engine Life (AEL)

NOTE: The factors are listed in their order of computation or derivation. Therefore, the crude failure rates were computed first and then used, directly or indirectly, to compute the remaining factors (40: Section II).

### TABLE 1. ACTUARIAL FAILURE FACTORS

ENGINE STATUS REPORT										RCS																											
1. ENGINE DESIGNATION TYPE NO. MODEL		2. ENGINE SERIAL NO. YR. MFR.		3. COMD. MAL. SUB.		4. ORG.		5. STATION NO.		6. ACCT.		7. RE- PORT		8. DATE YR. DAY		9. SEQUENCE NO.																					
10. TRANSACTION		11. CONDITION		12. TO OR FROM		13. CON- TAINER		14. TRANSPORTATION CONTROL NO.		15. REPAIRABLE ENG. SERIAL NO.		16. DOCUMENT NUMBER		17. MAP NUMBER		18. REMOVAL REASON		19. ENGINE TIME		20. 21.		22. 23.		24. 25.		26. 27.		28. END ITEM DESIGNATION		29. END ITEM SERIAL NO.		30. POSITION NO.					
GAIN		E SERVICEABLE		R		F		B		J		K		L		M		N		O		P		Q		R		S		T		U		V			
NEW PRODUCTION		A WORK COMPLETED		F RAW		G BUILT-UP		H		I		J REPAIRABLE		K WITH QEC		L WITHOUT QEC		M MAJOR		N MINOR		O CONDEMNED		P		Q		R INSTALLED		S ACTIVE		T INACTIVE		U		V	
REIMBURSABLE		B TEST CELL REJECT		G		H		I		J		K		L		M		N		O		P		Q		R		S		T		U		V			
NON-REIMBURSABLE		C WORK STOPPED		H		I		J		K		L		M		N		O		P		Q		R		S		T		U		V					
EXCHANGE		D WORK STARTED		I		J		K		L		M		N		O		P		Q		R		S		T		U		V		W		X			
LOSS		E REMOVED TRANSIENT		J		K		L		M		N		O		P		Q		R		S		T		U		V		W		X		Y			
ATTRITION		F REMOVED OTHER		K		L		M		N		O		P		Q		R		S		T		U		V		W		X		Y		Z			
FOR PARTS		G CHANGE IN MAINT.		L		M		N		O		P		Q		R		S		T		U		V		W		X		Y		Z					
SALVAGE/R-M		H WAIT DISPOSITION		M		N		O		P		Q		R		S		T		U		V		W		X		Y		Z		AA		AB			
OTHER		I		N		O		P		Q		R		S		T		U		V		W		X		Y		Z		AA		AB		AC			
NON-GAIN/LOSS		J		O		P		Q		R		S		T		U		V		W		X		Y		Z		AA		AB		AC		AD			
RECEIVED		K		P		Q		R		S		T		U		V		W		X		Y		Z		AA		AB		AC		AD		AE			
SHIPPED		L		Q		R		S		T		U		V		W		X		Y		Z		AA		AB		AC		AD		AE		AF			
TRANSFERRED		M		R		S		T		U		V		W		X		Y		Z		AA		AB		AC		AD		AE		AF		AG			

AF FORM 1534, JUL 68 PREVIOUS EDITIONS OF THIS FORM ARE OBSOLETE.

FIGURE 2 - AF FORM 1534, ENGINE STATUS REPORT

Engine operating hours, status, location, and condition were some of the data elements maintained by the D024 central engine master file. Engine operating time was reported on the AF Form 1534 quarterly for all installed engines as well as each time an engine was removed, received, or shipped. Engine removals, installations, and changes in condition (serviceable or reparable) were reported via AF Form 1534 as they occur. The D024 maintains these records for all AF engines by serial number in addition to serial numbers for F100 engine modules.

The F100 engine master records were also maintained by the G337, Cycle Reporting and Failure Tracking System, which incorporates the greater detail required to monitor the F100 modules and selected components (28:p.2-2). Status changes for G337 monitored components were recorded on AFTO Form 349, Maintenance Data Collection Record, by the responsible base-level maintenance activity and data from these actions were submitted to the G337 central site at OC-ALC for update of the F100 engine master file. F100 engine operating data were recorded from the Event History Recorder on AFTO Form 93, Modular Engine Time/Cyclic Accumulation Record (F100), and input to the Maintenance Management Information and Control System (MMICS) at base-level. This data updates MMICS records and the G337 master file. The G337 system provides the capability to interrogate F100 engine data to extract specific engine, module, or

component condition or life expended information (28:pp.2-2 to 2-4).

The C-5A Malfunction Analysis Detection and Recording Subsystem (MADARS) interfaced with the OC-ALC Ground Processing Segment (G081) to collect and trend selected performance data for the TF39 engine. The G081 maintained the TF39 engine master file containing serialized engine and component records similar to the G337 records for the F100 engine (28:pp.2-3 to 2-5).

In addition to the separate data systems developed for the F100 and TF39 engines, other AF engines have life-limited components identified which were monitored via manual records in addition to the D024 data. An example was the TF33 engine for the C141. Moreover, the TF41 and TF34 engines have been tracked through contractual arrangements with the prime manufacturers, Detroit Diesel Allison and General Electric, respectively (31; 37).

The MAJCOM EMs and ALC EIMs accomplish engine status monitoring through the use of D024 system output products. Among these were daily status, condition and location information, weekly not-mission-capable (NMC) status for each serial numbered engine on a worldwide and command basis, monthly failure and inventory data, and quarterly averages of pipeline time. An update of operating hours and inventory reconciliation was received quarterly from each AF engine reporting activity (42:Ch.2).

## Comprehensive Engine Management System (CEMS)

Rationale. The AF Inspector General reported in 1973 that the current engine data system was not responsive to major command needs (28:p.2-1; 37). The advent of the F-15 and A-10 aircraft with their modular and advanced technology engines created additional data system requirements for component tracking of hard time limit and low cycle fatigue items (31; 37). These facts coupled with known deficiencies in the existing engine data systems led to AFLC's initiation of the Comprehensive Engine Management System (CEMS).

The major cause of these deficiencies was attributed to lack of improvements in these data systems for approximately six years (28:p.2-1). Specific problems cited in the CEMS Functional Description (FD) were categorized into: duplication of data; manual data collection and analysis; and insufficient, inaccurate, and untimely data. The following lists specific examples of this categorization as drawn from the CEMS FD (28:pp.2-13 to 2-15):

### 1. Duplication.

a. Engine, module, and component records for condition, location, TCTO accomplishment, and operating hour data were maintained in more than one data system. Basic engines and modules were serially controlled by the DO24 for all engines, the G337 for the F100, and the G081 for the TF39. Moreover, other assemblies and parts were

tracked both by part number and serial number in separate systems. The above systems were separately maintained with distinct input requirements and procedures for each.

b. Engine performance information was collected and processed by these different systems which delays identification of engine problems.

2. Manual data collection/preparation.

a. Determination of engine overhaul and retention requirements necessitated manual research and computation.

b. Historical records for engines, modules, and components were manually prepared.

3. Sufficiency, timeliness, and accuracy.

a. There was no capability to correlate performance information and historical maintenance actions.

b. ALC and major command engine managers did not have an interrogation access to current maintenance data to determine historical information.

c. No data base existed to allow actuarial forecasting of the removal of selected components and future logistics requirements.

d. Current systems did not provide the scope, identification, or control during depot maintenance or overhaul necessary for accurate configuration management.

e. The quarterly collection of engine operating hours precluded effective interface with engine and

component requirement computation, workload projection, and asset distribution data systems. Moreover, major command engine managers were similarly limited by this untimely data when estimating deployment requirements and force status projections.

f. Weekly submission of base level TCTO accomplishment reports did not coincide with the D024 monthly TCTO status report. Consequently, TCTO completion data summary analyses were inaccurate and required manual research and correction.

Development Plan. The Air Force Logistics Command (AFLC) initiated CEMS development in 1977 due to the deficiencies in the existing system and to support the reliability centered maintenance (RCM) concept. CEMS objectives have focused on the improvement of asset visibility and, therefore, enhancement of AFLC's ability to direct and control the use of engine resources through the development of a single management information system for all commands and for all levels of engine management (4:10). Figure 3 depicts the CEMS interface between these levels (5). Engine history and maintenance data were projected to be transmitted from the existing base level computer to a central data base at Oklahoma City Air Logistics Center. Data analysis would be accomplished through an inquiry network comprised of mini-computers connected to the central data base computer

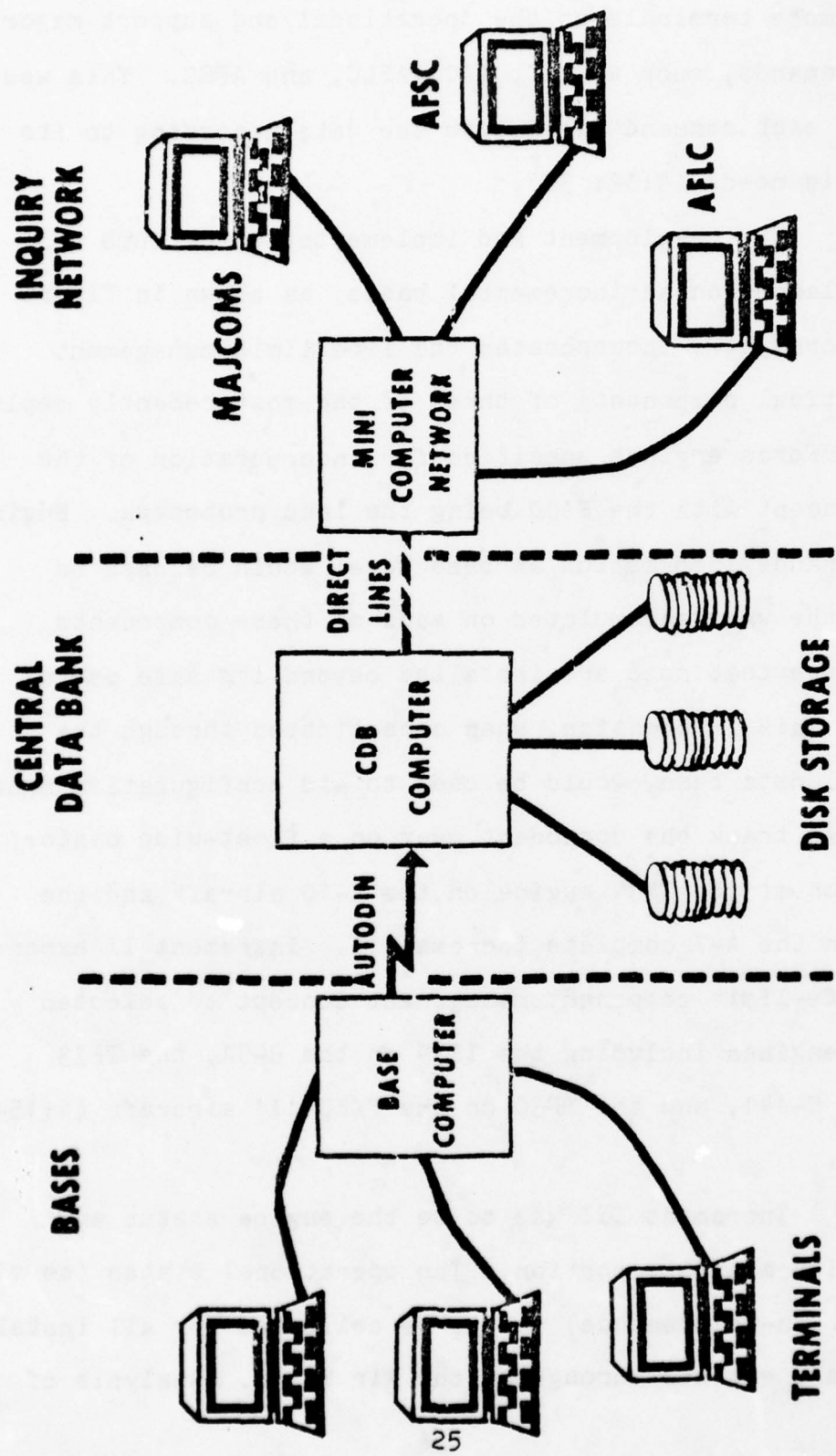


FIGURE 3 CEMS DATA INTERFACES (38).

and remote terminals at the operational and support major air commands, such as MAC, TAC, AFLC, and AFSC. This would permit each command to analyze the data according to its specific needs (4:12; 37).

The development and implementation of CEMS has been planned on an incremental basis, as shown in Figure 4. Increment I incorporated the life limit management of critical components of three of the most recently deployed Air Force engines specified for incorporation of the RCM concept with the F100 being the lead prototype. Engine maintenance information at base level would be used to track the wear accumulated on each of these components to ensure that none are installed beyond its safe useful life. This information, when consolidated through the central data base, would be used to aid configuration management and track the component wear on a fleet-wide basis. Addition of the TF34 engine on the A-10 aircraft and the TF41 on the A-7 complete Increment I. Increment II expanded the life-limit component management concept to selected older engines including the TF39 on the C-5A, the TF33 on the C-141, and the TF30 on the F/B-111 aircraft (4:15-17; 5; 37).

Increment III was to be the engine status and logistics analysis portion. The operational status (serviceable or in-maintenance) was to be collected for all installed and spare engines throughout the Air Force. Analysis of

INCREMENTS

- I. LIFE LIMIT MANAGEMENT (F100, TF34, TF41)
- II. LIFE LIMIT MANAGEMENT  
(TF39, TF33, TF30, J60, J85)
- III. ENGINE STATUS, BASE STOCKAGE AND ACTUARIAL ANALYSIS
- IV. ENGINE HEALTH MONITORING BY TURBINE ENGINE MONITORING  
SYSTEM (TEMS)

FIGURE 4 CEMS IMPLEMENTATION INCREMENTS (38).

this data would permit requirement determination of spare engine base stockage and new engine procurement. For modular engines such as the F100 and TF34, this determination would also apply to the component modules (4:15-17; 37).

Increment IV was to incorporate TEMS as an engine condition monitoring technique to improve the determination of maintenance requirements. The integration of TEMS with CEMS also will improve the data collection and analysis objective of CEMS to determine engine component useful life and further enhance achievement of the RCM concept (4:18; 31; 37).

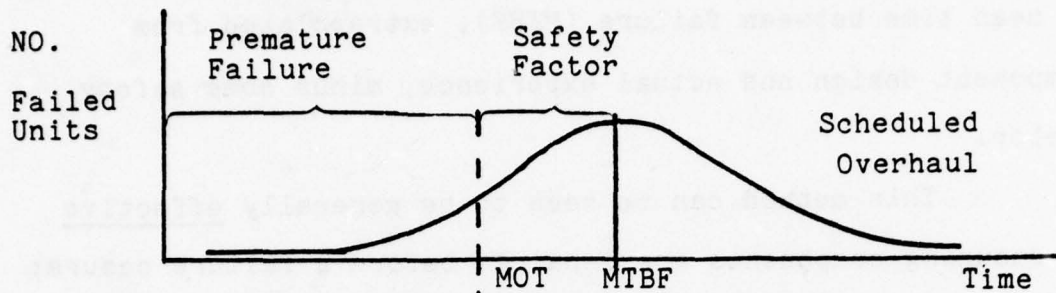
#### RELIABILITY CENTERED MAINTENANCE/ ON CONDITION MAINTENANCE

In general, maintenance actions on any piece of equipment are dictated by one of three criteria: (1) component or end item failure, (2) time interval since last repair or overhaul, or (3) indications of impending failure. Until the late sixties the airlines and the military services focused their primary aircraft maintenance efforts on the time interval, or scheduled maintenance, criteria. While the repair of failed components was an important source of maintenance requirements, especially at base level, the primary emphasis was the prevention of failures by developing maximum operating time (MOT) intervals which allowed the removal and replacement of components before

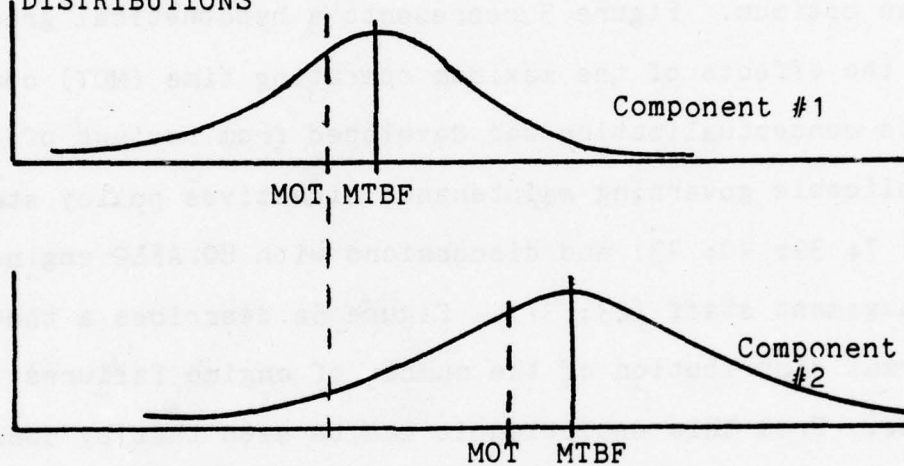
failure occurred. These intervals were based on the expected mean time between failure (MTBF), extrapolated from component design and actual experience, minus some safety factor.

This method can be seen to be generally effective in ensuring components are repaired before a failure occurs; however, its efficiency could easily be seen to be less than optimum. Figure 5 represents a hypothetical graph of the effects of the maximum operating time (MOT) concept. This conceptualization was developed from reviews of the applicable governing maintenance directives policy statements (3; 7; 39; 40; 43) and discussions with HQ AFLC engine management staff (23; 37). Figure 5a describes a theoretical normal distribution of the number of engine failures over time. From this depiction it can be seen that by conducting scheduled maintenance at MTBF less a safety factor, a majority of engines would have maintenance resources applied before it would be absolutely necessary; i.e., end of useful life. Moreover, Figure 5c, which depicts similar theoretical distributions for two components or modules, describes how the engine MOT can be the function of the component having the lowest MOT. Converting this into theoretical life terms, Figure 5b indicates that more than fifty percent of the theoretical engines could lose significant amounts their possible life (between maintenance actions) due to early scheduled maintenance.

### A. ENGINE FAILURE DISTRIBUTION



### B. COMPONENT FAILURE DISTRIBUTIONS



### C. ENGINE LIFE

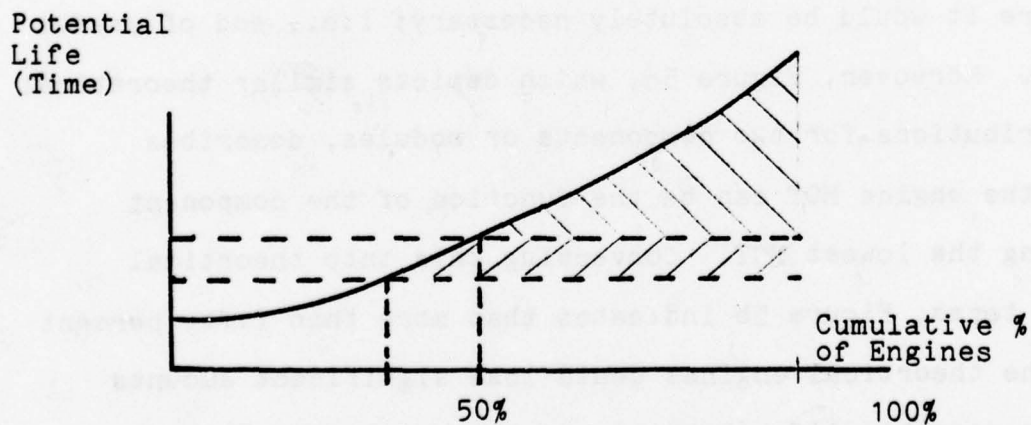


FIGURE 5 - EFFECTS OF MOT CONCEPT

To overcome this inherent shortcoming of the maximum operating time concept and to develop more efficient maintenance, the airlines and manufacturers devised a decision logic process (7:1). In 1968 the Maintenance Steering Group of the Air Transport Association of America issued Handbook MSG-1, Maintenance Evaluation and Program Development, which indicated the need for decision logic and airline and manufacturer procedures for the development of the maintenance program for the then new Boeing 747 aircraft. In 1970 the successful implementation of MSG-1 encouraged the steering group to rewrite the handbook into a more universal document, MSG-2, Airline/Manufacturer Maintenance Program Planning. Further, MSG-2 formed the basis for the DOD direction to implement "... an engineered, reliability-centered maintenance strategy... [38:p.III-417]." As the result of DOD direction and HQ USAF tasking, AFLC became responsible for integrating MSG-2 into Air Force logistics policy. Modifying the principles established in MSG-2 to accommodate the difference between flight operations of the military versus that of the airlines, a refined program termed Reliability Centered Maintenance (RCM) was launched in 1974 (6:1; 22).

#### Reliability Centered Maintenance Program (RCMP)

The Air Force defined the RCMP as:

A failure modes and effects analysis technique (FMEA) for significant aircraft and engine structures, assemblies and items. It uses a decision logic procedure based on the Airlines/Manufacturers' Maintenance Planning Document, MSG-2. This structured approach to maintenance requirements analysis, identifies minimum essential requirements consistent with safety and readiness [39:137].

The objective of this program was the development of a maintenance plan that "... prevents deterioration of the inherent design levels of reliability and operating safety ... at the minimum practical costs [7:37]." Expanding on this definition, the RCMP takes the inputs of the identified potential failure modes of an aircraft's systems, subsystems, or components and determines how these items will be maintained from a decision logic process based on the potential effects of a failure and the effectiveness and economy of the maintenance task needed to prevent the failure. This analysis classifies each component maintenance task into one of three categories: Hard Time Limit, On Condition, or Condition Monitored. These categories were defined as follows:

Hard Time Limit: A maximum interval for performing maintenance tasks. These intervals usually apply to overhaul, but also apply to total life of parts or units.

On-Condition: Repetitive inspections, or tests to determine the condition of units or systems or portions of structure.

Condition Monitored: For items that have neither hard time limits nor on condition maintenance as their primary maintenance process. Condition monitoring is accomplished

by appropriate means available to an operator for finding and resolving problem areas. These means range from notices of unusual problems to special analysis of unit performance. No specific monitoring system is implied for any given unit 7:3-47.

Thus, through the decision logic analysis only those components and maintenance tasks which have the most significant impact on operational safety or are economically impelling will be performed at periodic Hard Time intervals. Other items which are somewhat less significant are candidates for either the On Condition or Condition Monitored categories. Items for which there are means of detecting a reduction in failure resistance before undesirable systems effects occur may be scheduled or planned for the On Condition category. Failure resistance was defined as:

The deterioration of inherent (design) levels of reliability. As failure resistance decreases, failures increase; resulting in lower reliability. If reduction in failure resistance can be detected, maintenance can be performed prior to the point where reliability is adversely affected 7:207.

When no potential effective maintenance tasks are selected for scheduled (Hard Time Limit or On Condition) maintenance the component is placed in the Condition Monitored category.

#### On Condition Maintenance

On condition maintenance (OCM) could be described as a maintenance process used in "the physical performance of maintenance functions utilizing the maintenance plan developed under the RCMP (23; 39:12-13). Officially, the

US Air Force definition of on condition maintenance was: "Maintenance that allows the condition of the equipment to dictate the need for maintenance or the extent of repair/overhaul required [39:137]." The effective application of OCM at the three levels of Air Force maintenance (flight-line, intermediate, and depot) necessitated the development of effective inspection and monitoring techniques which could identify conditions of degraded resistance to failure and incipient failure (23; 37). Armed with these techniques, flight-line and intermediate maintenance personnel were to fault isolate to individual modules or line or shop replaceable units (LRU/SRU) and perform only those maintenance tasks which were necessary to correct deficiencies. Moreover, OCM allowed more tasks to be performed on the aircraft or in the intermediate shop rather than the item being removed and returned for depot overhaul (23; 31; 37).

OCM should also alter the depot maintenance process, especially for engines. Under the current overhaul concept, at a set maximum operating time (MOT) an engine is removed from service and returned to the depot for complete tear-down, inspection, component replacement, and reassembly in accordance with applicable technical orders. The operating age is then reset to zero on the assumption the overhaul process has returned the engine to like new condition (23; 37). The continued policy of complete engine overhaul

alone has been shown to be a critical cost burden to the Air Force (14:52-54).

Under OCM the depot complete tear-down and rebuild process would be replaced with a process including replacement of expired or near expired hard time components, inspections of on condition and condition monitored components with replacement or repair only as necessary, and analysis of engine health indicators to determine necessary maintenance actions. In summary, the depot maintenance process was to be tailored to the requirements of each engine versus the current standard work package for all engines.

Another important implication of the OCM/RCM process was that since engine maintenance was to be based on the categorization; i.e., Hard Time Limit, etc, of the engine's modules or components as opposed to the entire engine, the engine maximum operating time (MOT) was to cease to be the driving factor in determining the maintenance production schedule. This factor would become the Hard Time Limit or inspection schedule of individual components. Thus, the requirement to life or condition track individual components would have far reaching impact on the entire engine management system (15).

## ENGINE CONDITION MONITORING

### Objectives

New techniques and concepts have been developed and implemented to permit the transition from performing

maintenance on a maximum operating time basis to maintenance based on the RCM/OCM concept and to meet the operational need to reduce engine maintenance costs without jeopardizing mission reliability. Design and development of engines composed of modules was one recent example of these new concepts. Diagnostic engine monitoring had become a very attractive technique for assuring maximum aircraft availability at minimal system costs through the implementation of on condition maintenance practices for these modular engines as well as older, non-modular, turbine engines. These diagnostic systems were designed to supplement other established condition assessment techniques for maximum effectiveness. Among the many specialized diagnostic techniques are the Spectrometric Oil Analysis Program (SOAP), non-destructive inspection (NDI), periodic visual inspections, borescope inspections, and analysis of maintenance reports. When used in conjunction with these well established maintenance practices, a turbine engine monitoring system (TEMS) has been envisioned to form a total program of engine diagnostics which could determine the condition of a component, assembly, or system by visual inspection, measurement, test, or other method without requiring the engine to be removed from the aircraft and disassembled (13:2). One of the primary logistics objectives of TEMS has been to lower the engine component or subsystem maintenance category from Hard Time Limit to On Condition by providing aircrews

or maintenance technicians with the capability to detect reduced failure resistance as required in the RCM decision logic.

The Air Force TEMS Review Group, in a 1977 briefing to the Deputy Chief of Staff for Logistics Operations at HQ AFLC, specified several objectives for TEMS development and implementation. The Review Group had conducted an analysis of overall AF engine status, an evaluation of technical options, and a review of past TEMS as well as engine maintenance and safety data. The TEMS objectives established by the Review Group were categorized according to need: operational, maintenance, logistics, and safety (35).

Operational and maintenance objectives. The Review Group (35) proposed the following functional requirements for TEMS to fulfill the needs of aircrew and maintenance personnel:

1. TEMS should provide an advisory indication of overall engine condition in the form of a go/no-go advisory prior to flight.
2. The system should be capable of automatically detecting and recording engine operating characteristics which exceed established criteria. Recording at the pilots discretion should be permitted.
3. Any significant deterioration of engine thrust should be determined through gas path analysis.

4. The system should permit reduction of periodic engine inspections.

5. Maintenance trouble-shooting should be improved through the isolation of problems to specific areas or components of the engine.

6. The TEMS should aid engine performance adjustments or trimming following maintenance.

7. The flightline maintenance environment and support for the TEMS were strong considerations in the hardware characteristics specified by the Review Group. For example, the weight, durability, accessibility, and mobility of TEMS components should permit one-man operation. Also, components should not be subject to periodic inspections or calibration and should be reprogrammable without removal.

Although these objectives were specified by an Air Force panel, the TEMS operations reviewed herein have adhered to them in general; the primary differences being in the methodology used. These differences among selected AF systems are reviewed and discussed in Chapter III.

Logistics objectives. Achievement of on condition maintenance (OCM) for engines was the predominant logistics objective throughout the TEMS literature. Whether OCM was directive in nature (as within the DOD) or profit motivated, as in the commercial airlines, the consensus has been that

some form of TEMS is necessary to achieve the full benefit of OCM. However, other logistics objectives of TEMS included reduction of fuel consumption, prediction of engine spares and overhaul requirements, increased knowledge of engine component life-limits to reduce spares and overhauls, and improved engine management data (11; 31; 37).

Safety objectives. The specific safety objectives cited by the TEMS review group incorporated various aspects of the operational and maintenance objectives. For example, the mechanized collection and analysis of data for life-limited components plus the recording of out-of-limits conditions were to provide advance warning of impending catastrophic engine failures.<sup>1</sup> A major objective of the Strategic Air Command's manual engine condition monitoring program was to reduce in-flight engine shutdowns (33:11). Other safety aspects of TEMS included, go/no-go indications and inputs to crash recorders.

### Concepts

The technical feasibility of engine monitoring has been demonstrated by several tests conducted by the Military Services. Among these are the Navy's A-7 In-Flight Engine Condition Monitoring System (IECMS), the Army's

---

<sup>1</sup>Catastrophic failure: Sudden, unexpected damage or loss.

Automotive Inspection Diagnostic and Prognostic System (AIDAPS) for helicopters, and the Air Force's Engine Health Monitoring System (EHMS), which was tested on Air Training Command and Tactical Air Command T-38 aircraft. AFLC and TAC were currently evaluating the EHMS on A-10 aircraft at Myrtle Beach AFB, SC. Changes in the original T-38 EHMS caused AFLC to redesignate this particular application as the A-10 TEMS (31). These tests, and others, indicated that the TEMS concept was able to meet the required objectives. However, none of these systems or other system applications were identical in the method of data collection or in the analysis of the engine performance parameters monitored.

The identification of these parameters and the hardware necessary to monitor them reliably in an operating environment have been the subject of several research efforts sponsored by the Military Services and the Society of Automotive Engineers (SAE). The reliability question was addressed in a study by the Air Force Aero Propulsion Laboratory (AFAPL) which concluded that:

With only minor exceptions, sensors of acceptable accuracy and durability are available for diagnostic monitoring of engine parameters, and are considered to be satisfactory for diagnostic fault isolation and trending purposes at base level [1:2].

Parameter selection was, therefore, a managerial and/or engineering decision which was not limited by sensor technology.

Parameter development and selection. The basic elements of engine operation required for engine condition monitoring included the actual flight conditions under which the engine data was obtained, engine speeds and temperatures, and the mechanical condition of engines, accessories, and components (1). The following methods are used to gather engine related data:

1. Detection of out-of-limit conditions of engine parameters.
2. Trend analysis of selected parameters.
3. Gas path analysis to compute changes in engine parameters not directly measured.
4. Analysis of mechanical data such as vibration, fuel pressures, and fuel flow.
5. Recording and accumulating engine speed ranges for low cycle fatigue usage estimation.
6. Oil quality analysis.
7. Visual inspections, such as borescope and radiography.

The detailed selection of the parameters used in a specific TEMS application depended on the type and

complexity of the engine and its operational environment as well as the degree of fault detection, analysis, and diagnosis required (18:2). Consequently, a comprehensive list of essential parameters did not exist; however, all system applications used outside air temperature, airspeed, and altitude to establish aircraft flight conditions.

Gas path analysis and low cycle fatigue (LCF) were obtained from sensors which measured rotor speeds and internal engine temperatures and pressures. Mechanical condition was measured by vibration and oil quality among others (14:64-67).

As the desired parameters were identified, the type and location of the sensors designed to measure these variables were selected. In most cases, existing sensors used for cockpit indicators or engine controls were used in conjunction with additional sensors installed on the engine. The TEMS installations reviewed were retrofitted to existing engines or incorporated into the basic engine design as in the cases of the TF34 engine on the A-10 aircraft and the F100 engine on the F-15 (31).

Recording systems. Although the majority of existing engine monitoring systems used automatic monitoring and recording equipment, manual monitoring and trending had been used successfully by the Strategic Air Command on KC-135 and

B-52 aircraft (30). This manual monitoring and trending program appeared to have met the major TEMS objective of implementing the on-condition maintenance concept with the associated reduction in operational support costs (12; 29-11).

The methodology of automatic monitoring included selective versus continuous recording of engine data using on-board magnetic tape or electronic data storage components. Selective recording of specified portions of a normal aircraft mission or upon detection of out-of-limit conditions had the purpose of reducing data processing and analysis volume and also reducing the space required for on-board recording equipment. Selective recording systems were used primarily to meet TEMS operational and maintenance objectives while continuous recording systems, such as the British Engine Usage Monitoring System (EUMS), had been used to improve engine safety and reliability through expanded knowledge of the engine's operational environment translated into design engineering changes (8:9-10).

#### Major Impacts on Engine Reliability

The data collection parameters selected for inclusion in an overall engine condition monitoring program were intended to meet the TEMS objectives. The major factors which have historically caused the greatest impact upon

engine reliability have been low cycle fatigue, damage to the engine combustion or "hot" section vibration and the engine lubrication system (35). This section will review these factors to provide a definitional background and the potential impact of TEMS on the factors.

Low cycle fatigue. The AF Aero Propulsion Laboratory has defined low cycle fatigue (LCF) as the "... cumulatively induced strain damage occurring in the one-hundred to one-hundred thousand event cycles ... [16:17]," which occurs in the engine's rotating components, such as compressors discs, and rotors. LCF has long been recognized as one of the more important factors affecting the service life of these engine components and LCF usage monitoring had been of primary concern to military TEMS designers and users (13:24). This concern was due to the catastrophic failures caused by LCF and the potential for the loss of aircraft.

Then current methods of determining major component LCF life have been based on engine operating time and include a significant safety factor. Some methods used on multi-engine aircraft, such as the C-5A and large commercial aircraft, have related LCF to the number of takeoffs and landings. However, in general LCF monitoring methods were extremely conservative; moreover, there had been a great deal of uncertainty regarding the relationship between

cycles and a component's actual safe life. Military tactical aircraft experience a more severe flight environment and require more frequent throttle movements than do multi-engine cargo or passenger aircraft (11; 19; 31). As a consequence, recent TEMS applications in the Air Force, such as the F-15 EHR and A-10 ETTR, have emphasized the development and incorporation of automatic engine cycle recording for tactical aircraft (31).

Hot section monitoring. Another major concern of recent TEMS development has been the critical dynamic stresses and high operating temperatures on many engine components resulting from the higher thrust ratings and performance required of current military engines (12; 31). Therefore, there has been significant emphasis placed on the monitoring of engine hot or combustion section performance and history. Borescope inspections have been used to detect thermal fatigue and cracks within the hot section prior to failure. However, these inspections were dictated by interval and may not have detected rapidly growing cracks in the hot section. Therefore, TEMS has sought to complement the traditional borescope procedures with some type of airborne hot section monitoring to detect deterioration and to increase the knowledge of the dynamics of thermal fatigue (18:3).

Vibration. Analysis of engine vibration has served to establish the condition of gears and bearings operated in gearbox type assemblies. This analysis has been based on the concept that defects in these bearings and gears cause vibration each time the defect passes a bearing surface. Measurement of the frequency of this vibration and comparison with the normal engine vibration range has been used to isolate and replace the defective components before failure (18:11-14). Vibration analysis techniques were also used in the Northrop Electronics designed Engine Health Monitoring System (EHMS) as a means of detecting subtle rotor imbalances such as those produced by the loss of a compressor or turbine blade. These techniques have been used to detect the more obvious effects of foreign object damage (27:pp.4-2 to 4-4).

Lubrication. The TEMS Review Group identified the engine lubrication system as ranking among the top four contributors to engine maintenance actions and man-hours, engine removals, and engine caused aircraft accidents (35). The Spectrometric Oil Analysis Program (SOAP) has been in use for many years to aid in the detection of impending failures in oil-wetted parts. This procedure has involved the collection of engine oil samples which are processed to determine any increase in the wear of bearing surfaces by recording the concentration of wear particles in the sample. The engine users

were notified of changes which indicate the incipient failure of the engine or a specific component. The time required to transport and analyze the collected sample at a centralized laboratory, has prohibited the field level identification of these impending failures and has limited the effectiveness of this method (18:15).

TEMS Impact. Low cycle fatigue, the engine hot section, vibration, and lubrication have been among the most critical factors affecting engine reliability. Any improvement in the acquisition of in-flight data concerning these factors would enhance the prediction, detection, and diagnosis of failures associated with these factors. The TEMS Review Group concluded that the technical capability existed for TEMS to directly or indirectly measure these factors prior to any significant maintenance or safety impact (35).

#### Potential Benefits

A quote from a 1976 Technical Cooperation Program report, written by an Aeronautics Study Group representing five nations, summed up the potential benefits of engine health monitoring (EHM) systems:

There is absolutely no doubt that the right EHM system will contribute significantly to reliability, availability, and cost effectiveness of future aircraft and engines. Indeed, with the increasing sophistication of ... weapons systems, some form of EHM is rapidly becoming mandatory to minimize cost-of-ownership of these complex and expensive systems 234:287.

In contrast to this statement, a 1979 Rand Corporation report stated that the:

Benefits and costs of engine monitoring are still very uncertain. Quantitative benefits have not been realized, and costs have been higher than expected 28:197.

This uncertainty was primarily due to adequate control of variables and insufficient test time intervals. Consequently, TEMS benefits must be discussed in terms of the potential impacts on engine reliability, availability, and support costs although most TEMS applications have demonstrated the technical capability to automatically measure and record engine operating parameters. This section of the study presents a discussion of the potential TEMS benefits in the areas of engine operational availability, support costs, and safety with supporting data from specific TEMS applications.

Operational availability. The results of a study conducted by representatives from the Air Force Logistics Command, Air Force Systems Command, and the operational major air commands indicated that the not-mission-capable (NMC) condition of an aircraft could be attributed to the engine in 23.7 percent of the NMC conditions recorded during 1976-1977. The study also confirmed that the engine was the primary cause of aircraft nonavailability as compared to all other subsystems (35). The focus of the TEMS operational and maintenance objectives discussed in a previous section

was toward improvement of engine and, therefore, aircraft operational availability. The TEMS and its associated ground diagnostic equipment was intended to provide an indication of engine related problems plus verification of engine malfunctions identified by the aircrew. A TEMS was felt also to be able to identify the most probable cause of engine related problems thus speeding any corrective actions required and reducing maintenance turn-around time (14:4-5,11-28; 19; 31).

Analysis of benefits from several TEMS tests have indicated an increase of available flying hours from the same aircraft resources through the reduction in time the aircraft is undergoing maintenance. For example, the Navy's Inflight Engine Condition Monitoring System (IECMS) test resulted in a reduction in engine removals per 1,000 flying hours which translated into an average increase of 31.55 flying hours between removals of IECMS - equipped engines. Moreover, IECMS was credited with a reduction of the aircraft not-mission-capable rate for test aircraft (33:12-17).

The Air Training Command test of T-38 aircraft equipped with the Engine Health Monitoring System (EHMS) indicated improved operational availability due to more accurate fault isolation and reduced time required for engine trim operations. Engine trim time on the T-38's J-85 engine was cut by more than 80 percent due to the elimination or reduction of several maintenance operations.

A 60 percent saving in trouble-shooting time with EHMS resulted through the use of information available from the EHMS diagnostic test equipment which provided accurate data regarding engine problems and their causes. The EHMS also reduced teardown and inspection of engines which had experienced flameouts when the diagnostic system indicated the flameout did not result from internal engine problems (20:29-34).

Reports from commercial airlines which have implemented the Airborne Integrated Data System (AIDS) have been favorable regarding planned versus unplanned engine removals and other engine maintenance. Pan American Airways reported great improvement in forecasting engine removals based on predicted failures while Trans World Airlines indicated success with enroute engine maintenance scheduling based on AIDS diagnostic information (14:23).

Safety. An important collateral benefit of engine monitoring has been an improved safety environment. Improved fault isolation, the detection of malfunctions not identified by aircrews, and reduction of secondary engine damage were among the potential safety related features in addition to contributing to operational and logistics considerations (14:6). A study of Navy and Air Force A-7 aircraft accidents indicated that if engine diagnostic data had been available, 51 percent of the engine related accidents could have been

avoided (14:30). Specific cases of the ability of TEMS diagnostic data to enable the prediction and, therefore, prevention of engine or engine component failure to preclude the potential loss of the aircraft have been documented in several of the Air Force TEMS tests. For example, the following case occurred during the ATC test of the Engine Health Monitoring System:

After one flight, an EHMS instrumented T-38 indicated compressor and turbine damage. The pilot did not report a problem as the engine was operating well within performance limits. When the engine was torn down, the damage picked up by the EHMS was evident. A small piece of the combustion liner was missing, and there was minor damage to the first and second stage turbine buckets. When the piece broke loose and went through the engine, it changed the performance characteristics enough to alert the recording function of the equipment. Without the EHMS, additional, larger pieces of the liner could have broken off and caused major engine damage and possible loss of the aircraft [17:7].

In another T-38 EHMS case, the system confirmed a problem which was not readily apparent. The aircrew reported that the exhaust gas temperature (EGT) on one engine had exceeded its limit and had risen to 680 degrees for a period of one or two seconds. Analysis of the EHMS recorded data indicated that the over-limit condition was actually 779 degrees for 41 seconds. Without this analysis, the engine would have remained in service without maintenance action. Because of the EHMS indications, however, the engine was removed and the turbine was found to be severely

damaged. Any subsequent flight without engine removal would have resulted in engine failure and major aircraft damage (17:9).

The success of the Strategic Air Command's manual monitoring and trending system in predicting potential failures was typified by a case where the trend plot of a KC-135 engine indicated low turbine efficiency. Inspection of the engine detected burnt and bowed turbine nozzle vanes and an ineffective spray pattern from the fuel manifold nozzles. Repair of these deficiencies precluded potential secondary damage and a probable in-flight emergency due to engine deterioration (30:11).

Any improvement in flight safety through the use of a TEMS was also predicted to increase operational availability by conserving the critical resources of aircraft and combat trained crews. The military and airline engine health monitoring systems have demonstrated the technical capability to detect internal engine changes in time to apply the necessary preventative maintenance (11; 14:33-42; 31).

Logistics Support Costs. The USAF jet engine inventory consisted of 41,161 engines on 30 June 1978 according to the D024B, Propulsion Unit Item Inventory Management System. During a status briefing (5) to General Allen, AF Chief of Staff, on the Comprehensive Engine Management System (CEMS), the value of this inventory was placed at \$7.865

billion and was estimated to grow to \$14 billion by fiscal year 1984 when all F100 and TF34 engines were included in the inventory. Fiscal year 1978 engine support costs for spare engines, parts, and maintenance were briefed as being one billion dollars (5). The TEMS Review Group Logistics Committee reported that the engine was more costly to support than any other aircraft subsystem and that the engine components requiring the highest repair cost have varied by type of engine (35:3; 4). Degrande and Eickmann also identified the significance of the engine in overall weapons system support cost and further described the variation among different engine types that certain components, such as the compressor or turbine blades, had contributed to costs (14:43-45, 48-51). The Logistics Committee further stated that

... all engines consume a proportional share of the total support cost of any weapon system and are a prime candidate for meaningful cost reductions [35:27].

Many of the recent Air Force studies of engine condition monitoring had been directed toward reducing these support costs by improving maintenance fault isolation time, reducing secondary engine damage caused by component failures, and reducing fuel consumption through improvements in engine trim procedures. For example, an AF Aero Propulsion Laboratory report of the Advanced Diagnostic Engine

Monitoring System (ADEMS) stated that as an objective of the study

The ever increasing cost of engine overhaul and maintenance, ... have created a greater need for the development of improved diagnostic engine monitoring techniques (1:97).

The TEMS Review Group indicated that the installation of an in-flight TEMS on AF aircraft could reduce overall engine logistics support costs by approximately five percent with the most significant savings being in fuel, maintenance, and spares while minimally increasing inventory management and data processing costs (36).

The design and application of some of the early TEMS concentrated on improving engine reliability and performance, and although some specific systems met these criteria, and also provided some economic benefits, the cost effectiveness of an automated TEMS has not been conclusively determined to justify its fleetwide application. For example, the T-38 EHMS test conducted by ATC indicated that, although the EHMS reduced maintenance trouble-shooting (fault isolation) time and improved engine trim results, acquisition of an EHMS for retrofit of the ATC T-38 fleet was not cost effective (18; 20:43-56; 25:10-11). Moreover, Birkler and Nelson stated "... that the maintenance cost savings used to justify the F100 EDS are unlikely to materialize over the short term (8:v7)." The Strategic Air Command, however, claimed a \$6.2 million secondary damage cost avoidance from the in-flight manual monitoring program established fleetwide for KC-135 engines (29:11).

Although the Air Force's continued emphasis on TEMS development appeared unjustified when viewed on a strict cost effectiveness basis, the potential benefits relative to operational availability and safety are being considered in a total system approach (11; 31; 37). Birkler and Nelson commented on this approach by saying that:

... whether EDS passes or fails in the narrow sense of cost savings over the short term should not be the sole criterion on which it is judged. The potential benefits of anticipating needed maintenance, helping maintenance crews and engineering support personnel better understand engine failure cause and effect, and verifying that maintenance has been properly performed have substantial value. These benefits are especially significant now that the Air Force is moving toward an on-condition maintenance posture... 18:vi7.

Also, TEMS has been forecast to be an integral element of the Comprehensive Engine Management System by providing improved diagnostics of engine condition to enhance life- limited component tracking (4; 5).

## CHAPTER III

### ANALYSIS OF AIR FORCE TEMS APPLICATIONS

#### SYNOPSIS

Each of the AF TEMS applications reviewed during the research had the common objective of improving engine maintenance production. The systems which have been evaluated in service tests, those presently in operation, and the systems being proposed employed various means to accomplish this objective. The variations included differences in airborne and ground equipment, data collection and analysis, and presentation of diagnostic information. This section presents brief historical descriptions of the AF TEMS applications reviewed.

#### Background Descriptions

Past applications included the Engine Analyzer System (EAS), the Engine Health Monitoring System (EHMS), and the Advanced Diagnostic Engine Monitoring System (ADEMS). Systems currently in operational use included the C-5A Malfunction Detection Analysis and Recording Subsystem (MADARS), the Strategic Air Command's Engine Condition Monitoring program, the F-15 Events History

Recorder (EHR), and the A-10 Engine Time Temperature Recorder (ETTR). The F100 Engine Diagnostic System (EDS) was currently being evaluated for installation in F-15 and F-16 aircraft. The A-10 Turbine Engine Monitoring System (TEMS) was undergoing service test and flight evaluation at Myrtle Beach AFB SC.

EAS was a development and test program conducted by Aeronautical System Division (ASD). The twelve month service test involved EAS installation on 18 F-4C and 18-F105F aircraft and was completed in April 1967. The system was composed of a set of 20 sensors, a signal data converter, a computer/indicator, and a magnetic tape recorder. Sensor generated data, computed performance values, and documentary data such as engine serial numbers and date were continuously recorded. Analysis of tape recorded data was accomplished by special programs using existing on-base computer facilities. The tapes were duplicated and mailed to ASD for engine performance trending. The system also indicated potentially degraded engine condition through the display of eleven event flags on the face of the computer/indicator (21; 45).

The ADEMS program, conducted by the AFAPL, was an exploratory development program to evaluate a system specifically designed to enhance the operation and maintenance of an in-service engine. The system was installed on a TF39 engine of a C-5A aircraft at Altus AFB OK.

The test was not completed due to the destruction of the ADEMS equipment when the aircraft crashed and burned during an emergency landing in September 1974. Forty-six engine and airframe mounted sensors were used to collect the data used by ADEMS to monitor engine performance. Twenty-five of the C-5A/TF39 existing sensors and transducers were used. Other ADEMS airborne components included a Honeywell general purpose computer, logic interface modules, signal processors, a magnetic tape recorder, and an input/output printer. During the data acquisition process, preselected groups of data, such as oil system, vibration, or thermodynamic, could be selected for display on a remote control and display unit or printed on a keyboard terminal. Engine fault messages were displayed on the remote unit and printed on the terminal to identify deficiencies. Permanent recording on magnetic tape was accomplished during take-off, selected stable flight conditions, upon manual initiation and upon fault detection (10; 13).

AFLC has conducted two separate tests of the Northrop Electronics Division's EHMS on ATC and TAC assigned T-38 aircraft. Following the May 1977 completion of the first test at Randolph AFB TX, five of the ten EHMS equipped aircraft were transferred to Holloman AFB NM for the TAC test. EHMS monitored 35 engine performance and aircraft system parameters through 18 existing and

21 EHMS added sensors. Sensor inputs were continuously monitored to detect and record engine performance over-limit conditions. Four pre-set portions of each flight were recorded to generate data for performance trending purposes. Recorded data were stored in the on-board random access memory unit. A status panel indicated engine go or no-go condition which was determined by decision logic programs and limits programmed into the processing unit. A portable off-aircraft data display unit was used to transfer the recorded data for ground processing and presentation of detected over-limit events and diagnostic information (17; 20).

The Strategic Air Command has implemented a simplified engine performance monitoring and trending program involving in-flight recording of engine parameters by flight crews and analysis of performance trend plots by maintenance personnel. Initiated in October 1976 on KC-135 aircraft, the program has since been expanded to include the Command's B-52 and FB-111 aircraft. The program requires engine instrument readings to be manually recorded during a cruise portion of each flight. This data was then corrected and plotted on trending worksheets for each engine. The parameters monitored by this system were exhaust gas temperature, fuel flow, throttle position, oil consumption, engine rpm, and a subjective vibration index value. Baseline data was obtained from test cell and flightline test runs. Deviations

in the trended information indicate potential engine problems which require inspection to verify. Maintenance guidelines had been incorporated into a diagnostic guide. The major thrust of this manual monitoring and trending program was to predict impending engine failures before they occur and therefore reduce the cost of these failures. The continued use and expansion of the program were indicative of the achievement of this objective (29; 30).

MADARS has been in operational use on the Military Airlift Command's C-5A aircraft. The system was an integral part of the C-5A development and acquisition. Of the approximately 800 airframe and related subsystem parameters monitored by the system, 28 engine or engine related parameters were continuously monitored in-flight. Data was recorded when pre-selected limits were exceeded or upon command. Processing and analysis of recorded tapes was accomplished at Oklahoma City Air Logistics Center. Engine performance trending, updates of engine operating time, and low cycle fatigue counts were some of the outputs of this processing. MADARS engine data has been used to extend the TF39 engine overhaul interval. Unfavorable engine performance trends detected through the analysis of such parameters as EGT or inlet temperature were forwarded to the C-5A base maintenance organization for engine

inspection. MADARS data was also input to the aircraft crash recorder (13; 34).

The A-10 employed an Engine Time and Temperature Recorder for its TF34 engine. The ETTR was an electro-mechanical airborne recorder of hot section performance factors. The system measured turbine inlet temperature (TIT) and updates digital counters on the face of the ETTR. These counters were: elapsed engine time; the number of TIT excursions between 200 and 550 degrees centigrade, between 550 and 790 degrees, and between 740 and 810 degrees; and the elapsed time TIT reached or exceeded 790 and 810 degrees. Lights are used to indicate that temperatures greater than 840 and 927 degrees centigrade were exceeded. The ETTR also counted hot section factor (HSF) units which was an index directly related to stress occurring during engine operations. The TIT and HSF counts were manually recorded and forwarded to the engine manufacturer for analysis. The ETTR did not perform any on-board analysis of these counts but merely provided a logging method for record keeping and performance trending (31; 34).

The F-15 aircraft has employed an engine mounted Events History Recorder in conjunction with eight units of ground support equipment to accomplish on condition maintenance of the F100 engine. The EHR recorded and displayed eight engine condition factors. Four flags

provided an indication of an engine hot start based on TIT and RPM, TIT over-limit events, engine overspeed, and speed sensor failure. Four additional indicators displayed total engine operating time, two hot section time counters, and a low cycle fatigue counter. Maintenance actions generated by flag indications or aircrew comments were conducted through manual review of diagnostic logic trees which directed specific maintenance inspections or repair actions. Manual trend plots were used to identify defective F100 engine modules or provided an indication of EHR instrumentation problems. EHR and module replacement data were manually recorded and reported through the MMICS to the G337 data system for update of engine and module historical records (11; 13; 28; 31; 34).

The F100 Engine Diagnostic System was being developed by ASD for use on F-15 and F-16 aircraft. EDS would replace the then current EHR and five units of EHR support equipment. As planned, the EDS would monitor, compute, and record 42 parameters through engine and airframe sensors, multiplex units mounted on each engine, and an on-board data processor unit (DPU). An engine status panel was to be mounted on the aircraft to provide engine or EDS component go or no-go indications. Engine performance data would be recorded by the DPU upon detection of an exceeded limit at pre-set stabilized flight parameters,

or upon pilot command. Portable diagnostic display units (DDU) were to provide maintenance personnel with a fault detection capability when the status panel or aircrew reports indicated an engine problem. Diagnostic logic trees were to be pre-programmed in the DDU. The data collection unit (DCU) would permit collection of EDS generated data stored in the DPU from several aircraft for transfer to a central data system for analysis, trending, and record keeping. Flight test of the initial F-15 EDS installation was planned to begin in November 1979 at Langley AFB VA (11; 24; 31; 34).

The A-10 TEMS was a modified version of the Northrop EHMS used on the T-38 aircraft. The system was proposed to replace the then existing A-10 ETTR to provide automated recording and diagnosis of engine performance data. The data collection, processing, and analysis subsystems of the A-10 TEMS were similar to EHMS with the differences being primarily in the pre-programmed diagnostic routines and different parameter measurements. The service test was planned to conclude November 1979 following accumulation of 1400 flight hours (19; 32).

### Comparisons

A conceptual model was developed to describe TEMS operational characteristics and simplify comparative

analysis and identification of trends. This conceptual model is portrayed in Figure 6. Engine performance and other engine-related data are detected by sensors mounted on the engine or on the airframe. A signal converter transforms the sensor's signal into a digital form usable by an on- or off-aircraft computer. Parameters selected for use by the system are identified by the computer pre-programming as well as any decision logic criteria required for output processing. This criteria includes fault tree diagnosis or operating limits for specific parameters. Output may be in the form of recorded information, indications that maintenance is required, or both. The following sections use this conceptual model to describe the major features of the AF TEMS applications reviewed during this research.

Sensors. All of the automatic recording TEMS applications reviewed used existing and added sensors to accomplish the engine monitoring functions of each system. The SAC manual recording and trending system was excluded from this assessment as this system used data available from existing cockpit instruments. Approximately 30 sensors per engine were used by each system. Actual differences in the number of sensors per engine as well as the location of these sensors was attributed to the type of engine, such as turbojet or turbofan, monitored

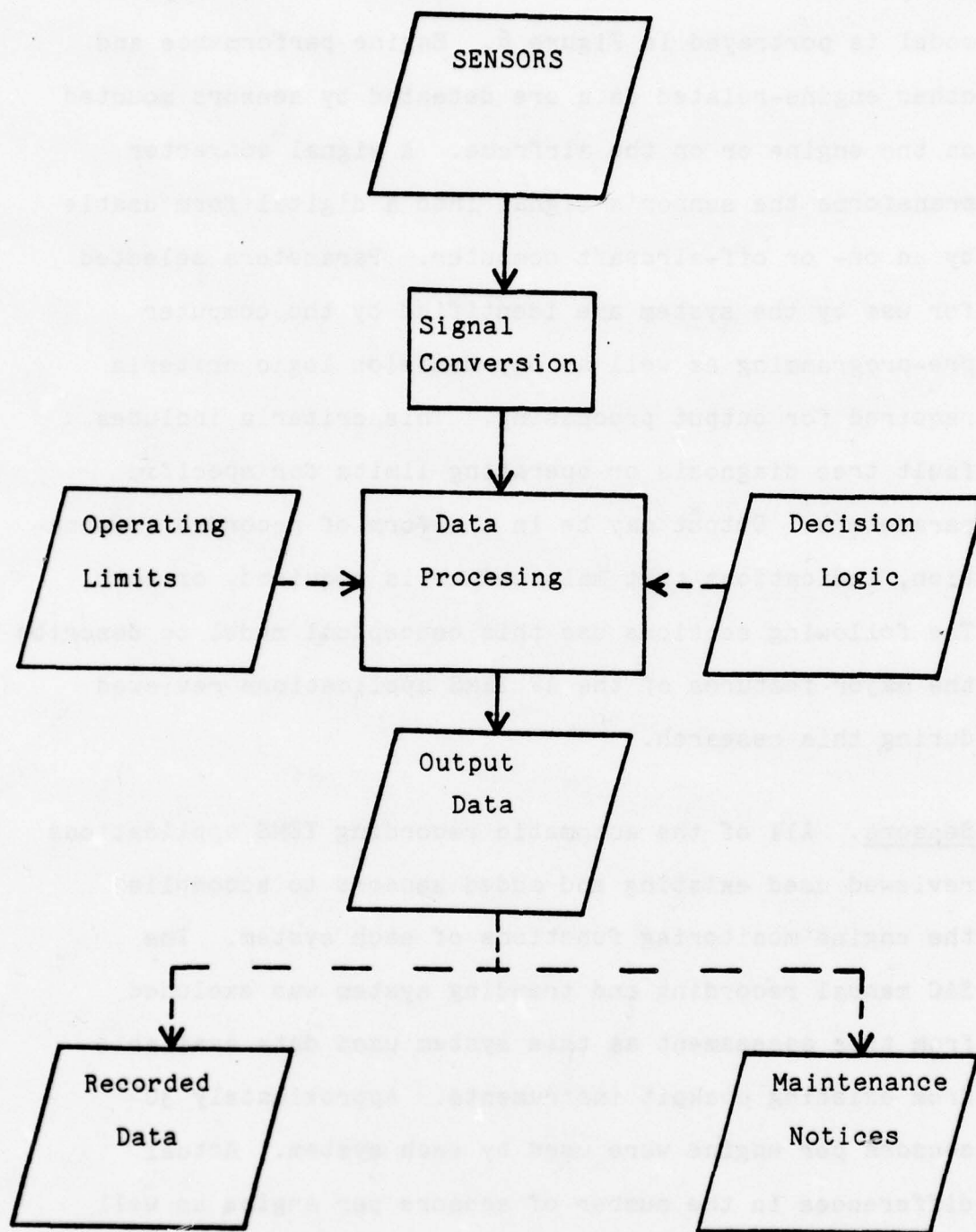


FIGURE 6 - TEMS CONCEPTUAL MODEL

by each system. In general, the turbojet engines, such as the J85 in the T-38 and the J79 in the F-4, used fewer sensors than the more complex turbofan TF39 and TF34 engines used in the C-5A and A-10 respectively.

Signal Conversion. The signal conversion process was again common among all the systems reviewed. The primary differences were identified in the location of the signal conversion units. The EAS, ADEMS, and EDS each used a separate component for signal data conversion while the EHMS and A-10 TEMS combine signal conversion and data processing functions into a single unit.

Data processing. Data storage and analysis were the areas where significant differences existed among the systems reviewed. The EAS, ADEMS, and MADARS used magnetic tape to record the data for further off-aircraft processing. The EHMS and A-10 TEMS used a separate memory core storage unit while the EDS combined the memory and processing functions into a single unit. This internally stored data was then transferred through connecting cables to portable off-aircraft data display or collection equipment. The SAC system, EHR, and ETTR required manual recording of data for trending or further analysis.

All of the automatic monitoring systems performed on-aircraft data analysis in varying amounts; however, the EHMS, EDS, and A-10 TEMS used off-aircraft components to complete data processing and presentation. The EAS, ADEMS, MADARS, and EHR analyzed engine over-limit conditions to provide the aircrew or maintenance personnel with indications of potential engine problems requiring off-aircraft fault diagnosis and isolation. The EHR, for example, used manual diagnostic charts to direct specific engine maintenance actions or inspections based on the EHR status panel flags.

Another major difference among the systems was the criteria used for recording in-flight engine performance data. EAS was a continuous recording system while the EHMS and A-10 TEMS recorded four pre-selected portions of each flight; pre-takeoff, takeoff, climb, and cruise. These two systems and EDS also recorded data when an exceeded limit event occurred and upon pilot activation of a cockpit switch. ADEMS and MADARS also selectively recorded engine performance data based on detected events and a portion of each flight.

Output. The forms, uses, and methods of presentation of TEMS output information varied significantly among the systems reviewed. Data was recorded on magnetic tape, stored in random access memories, and manually

transcribed. The EAS, ADEMS, and MADARS used magnetic tape as permanent records of recorded data for engine performance trending and fault diagnosis. The EHMS, EDS, and A-10 TEMS used on-board computer memories for temporary data storage prior to transfer to off-aircraft support equipment for diagnostic analysis and transfer to system related ground processing stations. These computer stations processed the data to create permanent records in the form of listings, paper tape, or magnetic tape.

Several TEMS applications also used engine status panels to provide maintenance personnel with immediate post-flight indications of potential engine problems. The volume of data presented ranged from the eleven engine performance indications on the EAS and the six flags used by the EHR to the two flag status panel used by the EHMS and A-10 TEMS to indicate system and aircraft go or no-go conditions. The portable diagnostic units of the EHMS, EDS, and A-10 TEMS contained fault isolation logic tree programs to provide identification of failed components or recommended maintenance actions.

### Trends

Through the system comparisons in the previous section, apparent trends were identified in the data processing and output elements of the TEMS conceptual

frame work. These trends indicated a movement toward greater dependence upon on-aircraft computer memory stored data and use of off-aircraft equipment for diagnostic analysis. The proposed EDS and A-10 TEMS were indicative of these trends as both were planned to replace existing event counter systems (the EHR and ETTR respectfully) with automated recording of engine performance data and detection of critical events. These systems were also both equipped with engine or system status indicators and employed portable off-aircraft diagnostic units to permit maintenance personnel to easily identify, validate, and correct TEMS and/or aircrew identified engine deficiencies.

## SYNTHESIS

The purpose of this section of the research analysis was to provide a synthesis of TEMS information available to the engine management system. The flow of engine performance data through each of the systems was analyzed according to the conceptual model in Figure 6. Categorizations of the relevant input and output parameters and the potential uses of these parameters were developed from this analysis.

The parameters used in the data processing segment of each system were reviewed and classified into general terms. For example, different terms were used among

the systems to describe the engine speed or revolutions parameter and these were classified under the general term rotor speed. These generalized parameters were then each categorized according to its respective portion of the monitoring process. These categorizations are listed in Table 2.

Documentary parameters provided references to identify recorded data. The environmental parameters were used by the TEMS to provide information about atmospheric conditions and also to compute portions of the gas path data. The gas path parameters measured the engine's thermodynamic performance while the mechanical parameters provided data regarding engine-related accessory equipment.

Table 3 presents a further categorization of the gas path and mechanical parameters according to uses within the engine management system. The fault isolation and trim categories included those parameters which were used by the TEMS to detect when established engine operating limits were exceeded, perform diagnostic processing, and check for proper engine operation following maintenance. These categories were primarily used in the performance of flight-line and JEIM maintenance production tasks. The history category concerns the engine management record keeping task and, when used with the trending

Gas Path

Engine Inlet Temperature  
Engine Pressure Ratio  
Exhaust Gas Temperature  
Exhaust Nozzle Area  
Turbine Inlet Temperatures  
Rotor Speed  
Guide Vane Position  
Anti-Ice Switch Position  
Afterburner Switch Position  
Compressor Discharge Pressure  
Compressor Discharge Temperature  
Power Lever Angle  
Vibration

Documentary

Engine Serial Number  
Aircraft Serial Number  
Flight Number  
Date

Environmental

Outside Air Temperature  
Outside Air Pressure  
Altitude  
Airspeed

Mechanical

Oil Temperature  
Oil Pressure  
Fuel Pressure  
Fuel Flow

TABLE 2. ENGINE PARAMETER CATEGORIES

Category of Use

<u>Parameter</u>	<u>Fault Isolation</u>	<u>Trim</u>	<u>Trend</u>	<u>History</u>
Engine Inlet Temperature	X	X	X	
Engine Pressure Ratio	X	X	X	
Exhaust Gas Temperature	X	X	X	X
Exhaust Nozzle Area	X	X	X	
Turbine Inlet Temperature	X	X	X	X
Rotor Speed	X	X	X	X
Guide Vane Position	X	X		
Anti-Ice Switch	X	X	X	
Afterburner Switch Position	X	X		
Compressor Discharge Pressure	X		X	
Compressor Discharge Temp.	X		X	
Oil Temperature	X			
Oil Pressure	X			
Fuel Pressure	X			
Fuel Flow	X			
Power Lever Angle	X	X	X	X
Vibration	X	X	X	

TABLE 3. PARAMETER USE CATEGORIES

parameters, form a historical data base from which engine performance trends were developed and tracked.

The development of these parametric categorizations and analysis of the flow of data through the various TEMS reviewed during this research led to the synthesis diagram depicted in Figure 7. Data from the TEMS sensors were collected as direct measurements of engine or engine related component operating performance. Some of the measurements were normalized to standard conditions or used to compute other measurements. These direct and computed measurements comprised the basic data available from TEMS. Elements of this basic data were used to detect variations in certain engine parameters which exceeded specified limits or reference values. The exceeded limit events were used to cause indicator flags to be set which display a detected event condition to maintenance personnel. The engine operating condition which triggered the event was also recorded for analysis. Certain of these detected events were used by pre-programmed or manual analysis routines. Diagnostic logic diagrams permitted the detected event to be compared to other parameter values or limits to aid in identification of the cause of the event. The information output from this process was in the form of raw data, detected events, and diagnosed conditions and was available to the AF engine management system.

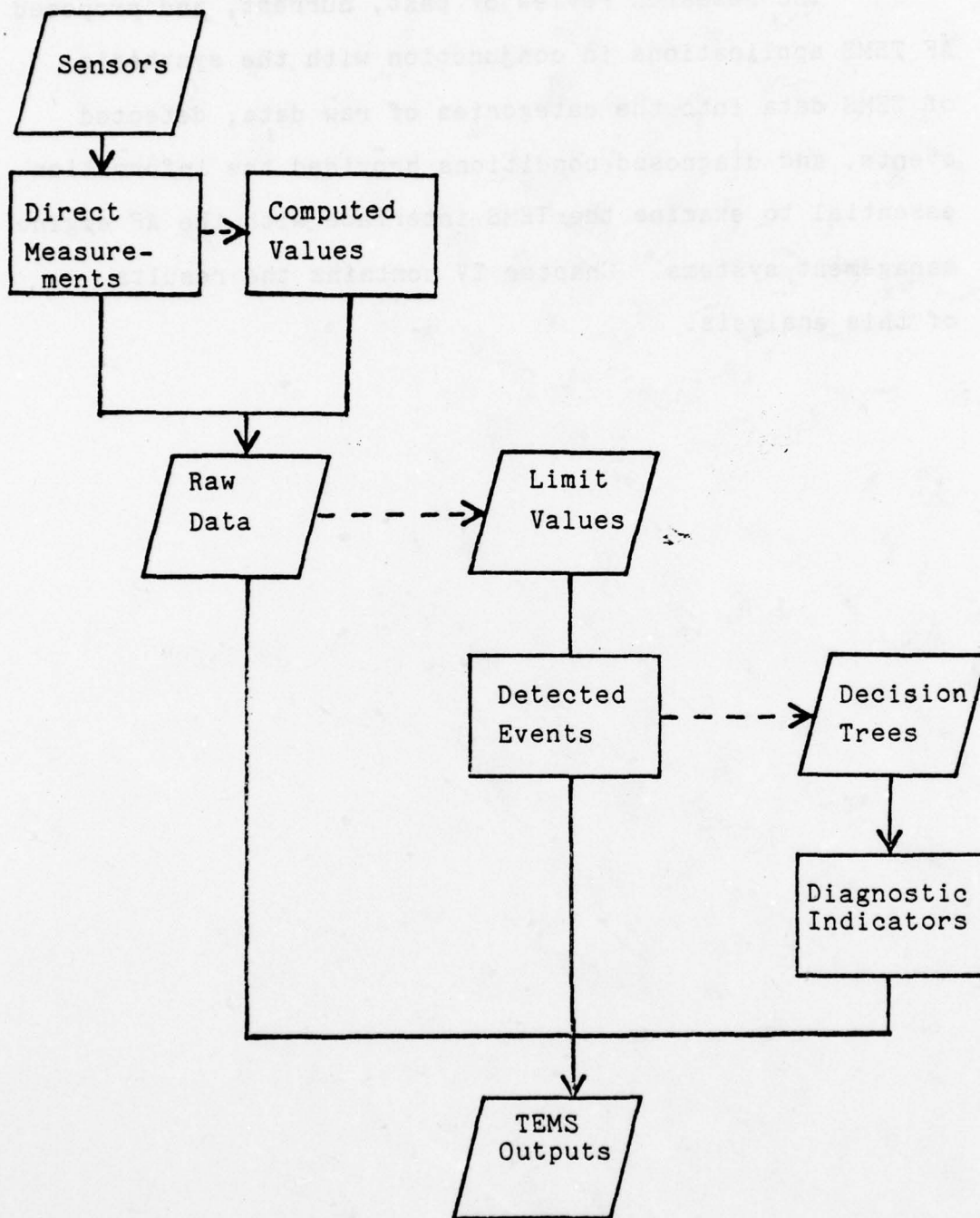


FIGURE 7 - SYNTHESIS OF TEMS OUTPUT

The research review of past, current, and proposed AF TEMS applications in conjunction with the synthesis of TEMS data into the categories of raw data, detected events, and diagnosed conditions provided the information essential to examine the TEMS interface with the AF engine management systems. Chapter IV contains the results of this analysis.

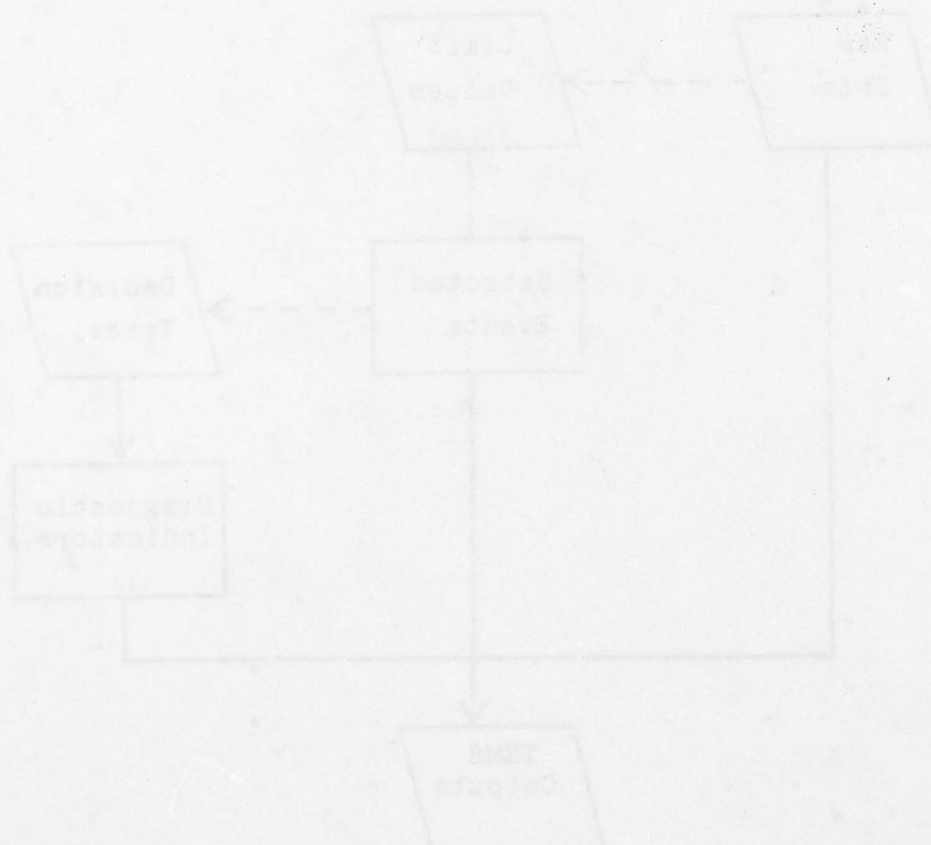


FIGURE 7 - SYNTHESIS OF TEMS DATA

## CHAPTER IV

### TEMS INTERFACE WITH ENGINE MANAGEMENT

#### INTRODUCTION

The interface and potential benefits of TEMS with the maintenance production levels was being examined in on-going tests of systems currently under development. This interface generally involved the supplementing of Technical Orders (TO), which tell maintenance personnel how to make a repair, with a system which:

... provides accurate identification of what components require repair and/or replacement, and reduces dependence on human judgment as to when this action must be initiated 26:47.

Moreover, the TEMS objective of increasing the knowledge of engine component life-limits has been documented in the engineering literature. However, the interface of TEMS with the engine management system described in Chapter II, and the objective of improving engine management data was only in the infancy of its conceptual stage of development (37).

To analyze the potential TEMS interface with the engine management system it was necessary to compare the information and data output from TEMS with information and

data needed to accomplish the engine management functions of inventory control and requirements determination. Moreover, since TEMS was integral to the implementation of RCM/OCM it was also necessary to include in the comparison the relationship of RCM/OCM to engine management.

#### TEMS OUTPUT

In Chapter III three basic types of information output by TEMS were identified. First, it produced raw data in the form of documentary, environmental, and performance measures of various subsystems, components, modules, and the engine in its entirety. This data consisted of measures of temperatures, pressures, rotor speed, and flow rates at various points in the engine operating cycle. The TEMS data processor logic also produced various computed raw digital data in terms of ratios and percentages which indicated the operating levels and efficiency of the engine. The second type of information produced by TEMS was the occurrence and duration of an over-limit events based on a comparison of raw data with pre-set limits. The third type of information produced was diagnostic indicators, derived from decision logic applied to raw data and detected events, which informed the maintenance production personnel that a component or module may be in a fault or failure and what that subsystem, component,

or module might be. Each type of information can be related to the engine as a whole and to specific components, modules, or combinations of these within the engine. Thus, TEMS provides data and information to each level of maintenance indicating the what and when of failures, which were then translated into the maintenance task (how) to correct the deficiency or failure. Furthermore, TEMS data and information could be related to operating time to produce trends of various parameters over time. This information could be used to further refine the effectiveness and efficiency of the prescribed maintenance tasks. This latter use of TEMS data (trending) could be classified as an element of the maintenance engineering function, as opposed to maintenance production, of the overall maintenance management. Examples of each of these types of information are presented in Figures 8 through 10 for the T-38 EHMS TEMS.

Therefore, if the engine management system was to integrate TEMS data, as envisioned in Increment IV of the Comprehensive Engine Management System (CEMS) (4; 5), it must have the capability to accept, and use for forecasting purposes, performance data based on temperature, pressures, and efficiency ratios at specific points in time. Moreover, CEMS must be able to use information produced by trended TEMS raw data, which depicts subtle

PAGE 1				PAGE 2			
FLIGHT NUMBER 1      APRIL 16, 1973				FLIGHT NUMBER 1      APRIL 16, 1973			
A/C NO 8191   LEFT ENGINE NO 961   RIGHT ENGINE NO 890				A/C NO 8191   LEFT ENGINE NO 961   RIGHT ENGINE NO 892			
FLIGHT DURATION 1 HR 38 MIN				FLIGHT DURATION 1 HR 38 MIN			
NO HALT/AV EVENTS ON THIS FLIGHT				TAKE OFF			
ALT 600 FEET      A/S NGOT 129      TIME 0 HR 00 MIN				ALT 600 FEET      A/S NGOT 129      TIME 0 HR 00 MIN			
LEFT		RIGHT		LEFT		RIGHT	
N ACTUAL	99.5	100.3		N ACTUAL	99.5	100.3	
N NORMAL	97.8	98.5		TS	EQ. 1.003	1.005	
CPR	6.11	6.13		CPR	EQ. .965	.968	
P AMR	PSI 14.38	14.38		EPR	EQ. 1.014	1.013	
VF NORM PPH	2610	2736		VF/PS3	EQ. 1.042	1.100	
VF	PPH 2455	2568		VF	EQ. 1.014	1.005	
TS	DEG C 25	25		PS3/PS5	EQ. .952	.920	
TS	DEG C 486	707		TS-VF	EQ. .000	.000	
IGV	8	8		PT2	PSI 13.57	13.55	
NOE AREA	8	70		PS3	PSI 22.9	23.0	
OIL PRESS	39.1	36.1		PS5	PSI 26.9	27.9	
ACCEL	.00	.00		OIL TANK C	69	73	
PWR LEV	114.0	115.0		STRESS	0	0	
COMP VIB	0	0		HYD TEMP C	40	42	
PTO	PSI 14.77	14.77		HYD PRESS	3004	3036	

## DOCUMENTARY DATA PAGE

## TAKEOFF DATA PAGE

PAGE 3				PAGE 4			
FLIGHT NUMBER 1      APRIL 16, 1973				FLIGHT NUMBER 2      MARCH 17, 1973			
A/C NO 8191   LEFT ENGINE NO 961   RIGHT ENGINE NO 890				A/C NO 8191   LEFT ENGINE NO 961   RIGHT ENGINE NO 890			
FLIGHT DURATION 1 HR 38 MIN				FLIGHT DURATION 1 HR 27 MIN			
IN FLT.				RANDOM			
ALT 20000 FEET      A/S NGOT 303      TIME 0 HR 34 MIN				ALT 3000 FEET      A/S NGOT 305      TIME 0 HR 15 MIN			
LEFT		RIGHT		LEFT		RIGHT	
N ACTUAL	100.6	101.0		N ACTUAL	98.2	98.1	
N NORMAL	101.0	100.3		TS	EQ. .840	.970	
CPR	6.46	6.38		CPR	EQ. .871	.924	
P AMR	PSI 6.78	6.78		EPR	EQ. .841	1.037	
VF NORM PPH	2036	2000		VF/PS3	EQ. 1.042	1.077	
VF	PPH 1648	1670		VF	EQ. 1.000	1.030	
TS	DEG C 0	0		PS3/PS5	EQ. .981	.985	
TS	DEG C 606	700		TS-VF	EQ. .000	.000	
IGV	8	0		PT2	PSI 6.00	6.00	
NOE AREA	8	11		PS3	PSI 25.0	24.4	
OIL PRESS	33.0	20.3		PS5	PSI 17.3	18.2	
ACCEL	.00	.00		OIL TANK C	103	113	
PWR LEV	98.5	89.1		STRESS	0	0	
COMP VIB	0	0		HYD TEMP C	43	50	
PTO	PSI 6.09	6.09		HYD PRESS	3004	3013	

## FLIGHT DATA PAGE

## PILOT ACTUATED SAMPLE DATA PAGE

FIGURE 8      EXAMPLE: T-38 EHMS RAW DATA OUTPUT (27:p.7-5).

Detected Event

Hot Start  
Exhaust Gas Overtemperature  
Vibration Front Frame  
Oil Pressure Low  
Oil Temperature  
Nozzle Area Error  
A/B Rollback RPM Low  
Overspeed  
Fuel Pressure  
Stall/Flameout

Diagnostic Indicator

Compressor Damage  
Burner Damage  
Turbine Damage  
Afterburner Section Damage  
Main Fuel Control Defect  
Inlet Guide Vane/Bleed Valve  
Anti-Ice Valve  
Stall Margin Increase  
Thrust Reduced

FIGURE 9 - EXAMPLE T-38 EHMS EVENT AND DIAGNOSTIC  
OUTPUTS (26:32)

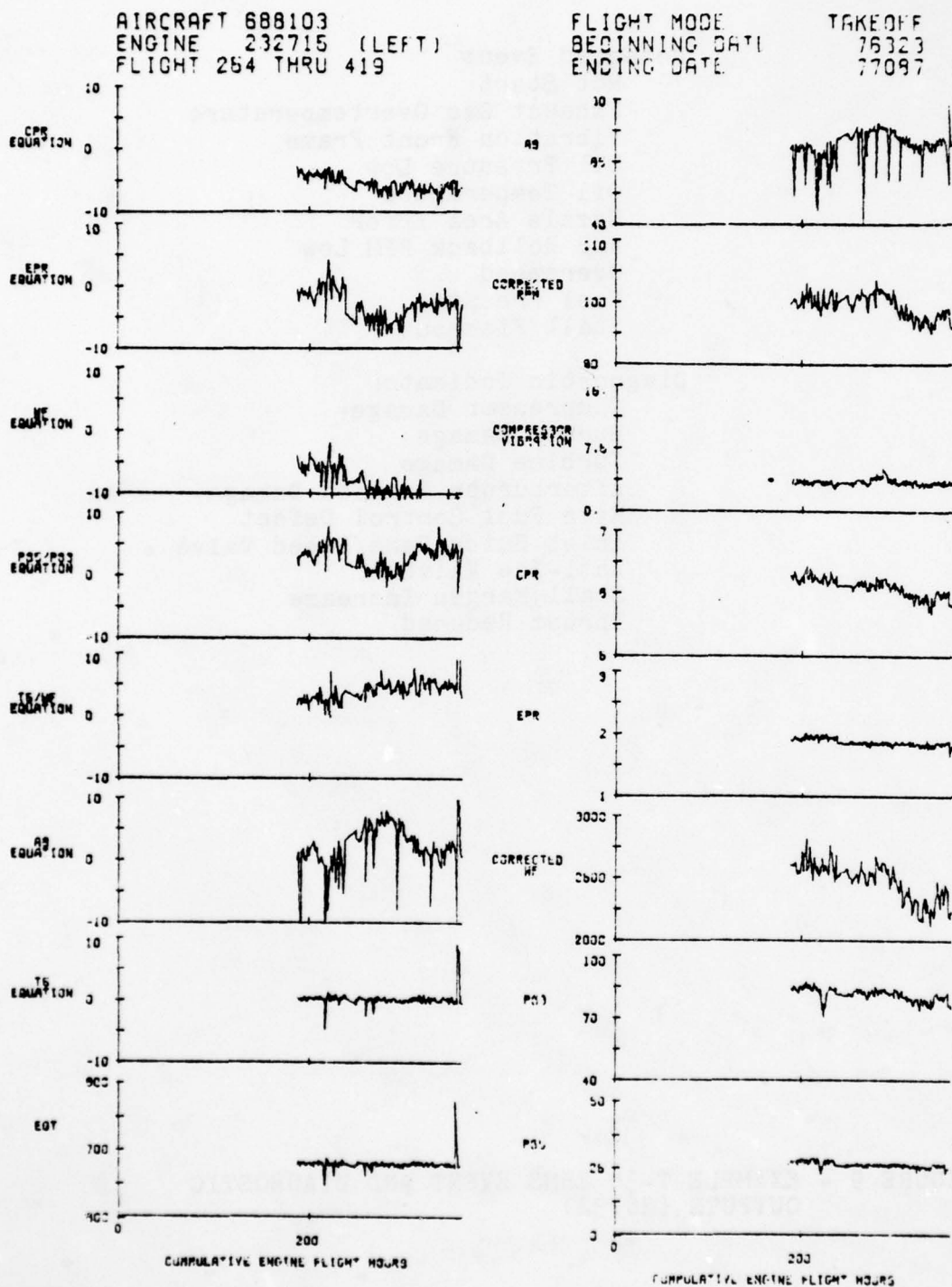


FIGURE 10 EXAMPLE: T-38 EHMS TRENDING RAW DATA (25:36)

AD-A077 531

AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL--ETC F/6 21/5  
AN ANALYSIS AND SYNTHESIS OF ENGINE CONDITION MONITORING SYSTEM--ETC(U)  
SEP 79 J W CHAPMAN, C L PAGE

**UNCLASSIFIED**

AFIT-LSSR-27-798

NL

2 OF 2

AD  
A077531

1000

END  
DATE  
FILMED

12-79

DDC

changes in engine, module, or component performance over a period of time. In general, CEMS must have the capability to convert TEMS performance engineering data or individual and groups of similar engines into predictions of spares and workload requirements.

#### RCM/OCM INTERFACE CONSIDERATIONS

One of the primary objectives of TEMS is to facilitate the implementation of Reliability Centered Maintenance (RCM), as related to maintenance engineering, and On Condition Maintenance (OCM), which is the maintenance production phase of the RCMP. Thus any examination of the TEMS interface must be made in the context of the effects on the engine management system of RCM/OCM.

Based on the research, two RCM/OCM principles appear to affect and require changes to the current engine management system. First, ending maximum operating time (MOT) as the criteria for engine overhaul, will significantly affect the actuarial method of forecasting engine removals. Recall from Chapter II that Actuarial mathematics are based on the assumption that the probability of an engine removal is a function of the engine age, and that this age is measured over an interval from the time an engine was newly acquired or completely overhauled to an arbitrary maximum age at which time it could be reasonably expected

that all engines would have failed or would require complete overhaul (40:p.2-1). This arbitrary maximum age has been MOT for each TMS engine. Ending the policy of engine overhaul due to MOT is analagous to making a human's life indefinite by changing his defective parts, such as liver, heart, kidney, etc, whenever one of these fail. Under RCM/OCM, an engine's life will be indefinite since only its defective parts being changed when needed and complete overhaul will be accomplished only when the engine experiences catastrophic damage due to foreign object damage or accident. Therefore, new methods will be needed to replace or modify the acturial method of forecasting.

The second RCM/OCM principle affecting engine management is that instead of the maximum operating time overhaul policy, engines will be repaired and components or modules replaced to the extent indicated by the condition of the overall engine and its individual components and modules. The components and modules themselves, will be repaired based on their categorization as Hard Time Unit, On Condition, or Condition Monitored. Thus the engine management system will not only be required to maintain records on, monitor, and forecast requirements for whole engines, but also perform these tasks for the engine components and modules. Moreover, the system

will be required to record which serially numbered components or modules are installed in each particular engine and when these items are removed from each particular engine. Additionally, the classification of some components and modules as On Condition and Condition Monitored will require similar changes to actuarial methods to accomplish the forecasting task.

## INTERFACES WITH ENGINE MANAGEMENT

### Current Maintenance Interface

As discussed in the literature review of Chapter II, the current interface between the base or operating level and the engine management system is governed by AFM 400-1, Volume II, Engine Status Reporting. This interface is depicted schematically in Figure 11.

Figure 11 shows that various inputs such as aircrew trouble reports, inspections, and scheduled maintenance actions are translated into maintenance production tasks which represent engine servicing, or engine removal. These removals, and all flying hours incurred since last overhaul are reported via the AF Form 1534, and recorded by the engine management system. The data thus generated and maintained forms a basis for monitoring the engine inventory and developing actuarial factors for the forecasting task. Moreover, the maintenance engineering function

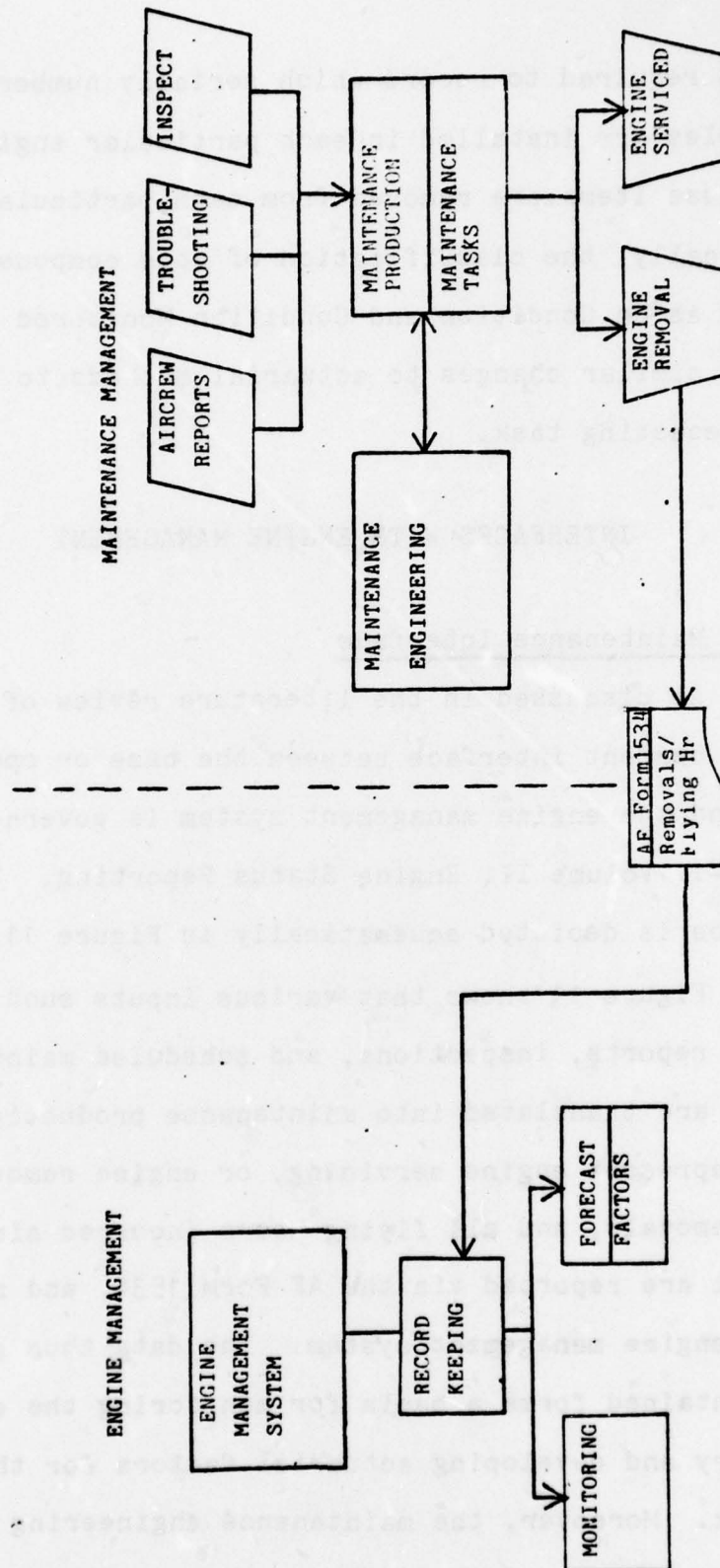


FIGURE 11 - CURRENT MAINTENANCE - ENGINE  
MANAGEMENT INFORMATION INTERFACE

obtains data in the form of deficiency reports from the maintenance production function (39:3-4).

#### Current TEMS Interfaces

An initial objective of TEMS was to improve the efficiency of flight line maintenance. As systems, such as EDS move into the full scale production and deployment phase, TEMS will also provide additional data into the maintenance engineering function. The current interfaces are illustrated in Figure 12 and were reviewed in the On Condition Monitoring Section of Chapter II.

#### PPROJECTED TEMS-CEMS INTERFACE

Based on the foregoing discussion of TEMS outputs, RCM/OCM considerations, and current maintenance and TEMS interfaces, the potential TEMS-CEMS interface envisioned by Increment IV of CEMS development and depicted in Figure 13 can be examined. This examination was structured using the three engine management tasks of record keeping, monitoring, and forecasting.

#### Record Keeping Task

The combined effect of TEMS and RCM/OCM will be to expand both the volume and the complexity of the record keeping system. Using the T-38 EHMS as an example,

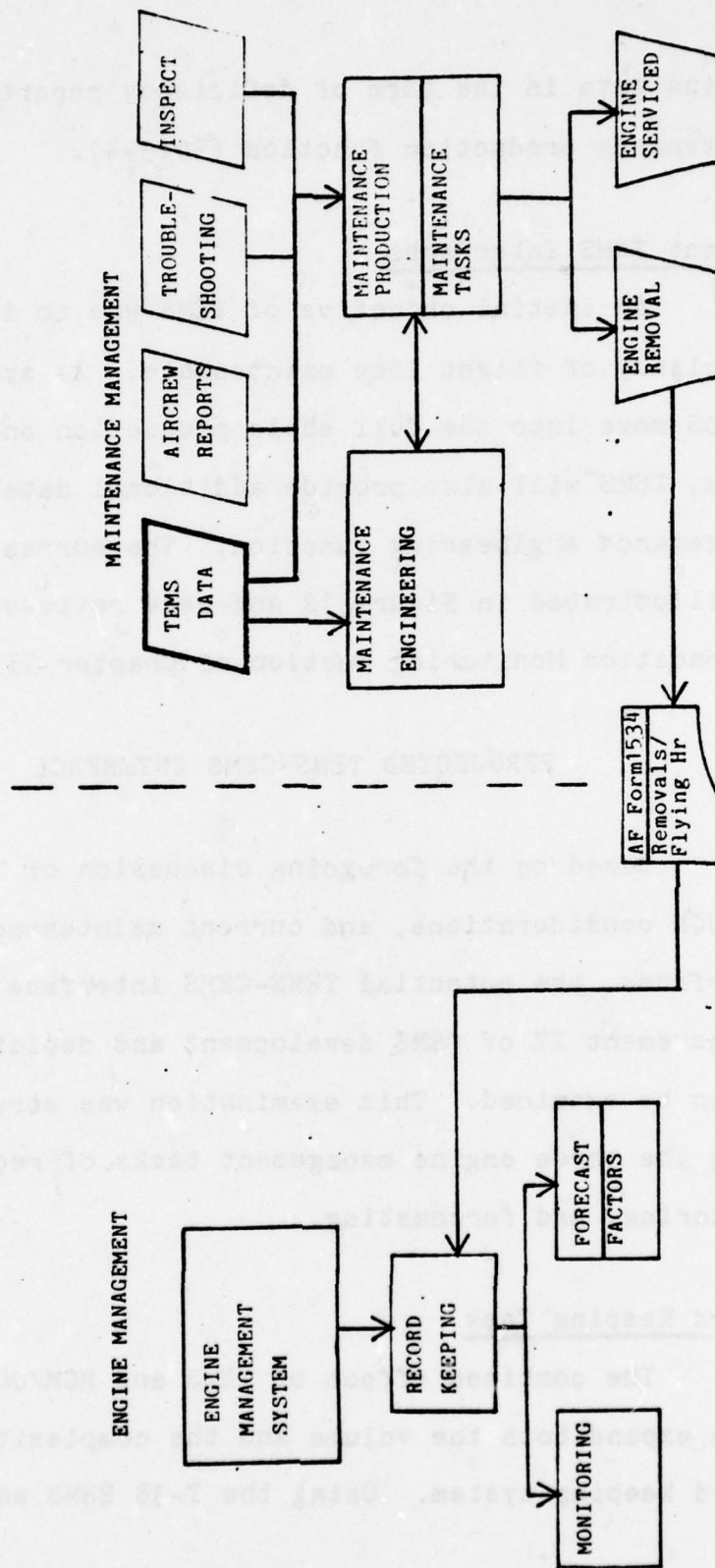


FIGURE 12 - CURRENT TEMS INTERFACE (ADDED)

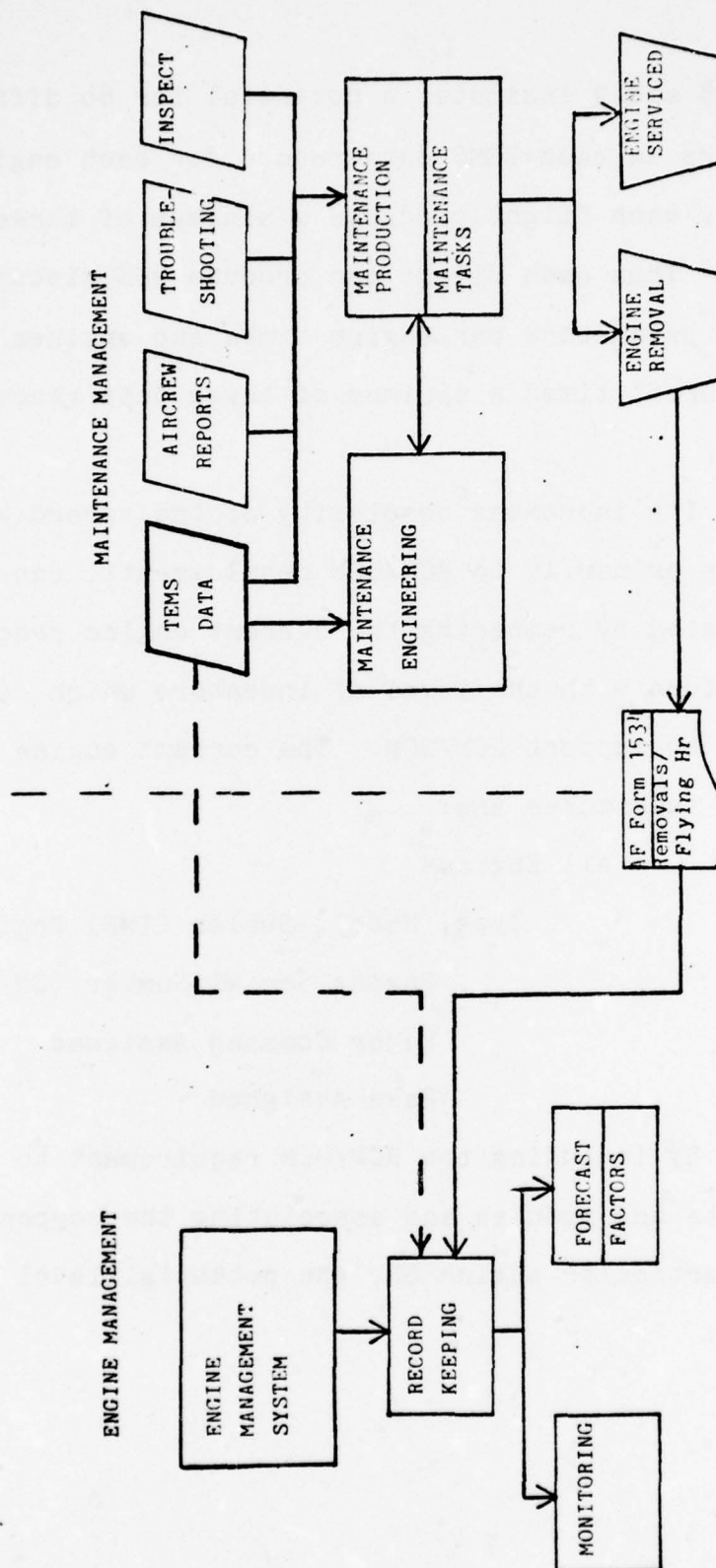


FIGURE 13 - ENVISION TEMS-CEMS INTERFACE (ADDED)

Figures 8 and 9 indicate a potential for 68 different parameters in each TEMS data record for each engine. Moreover, each flight produces a minimum of three data records. Thus each flight can produce 408 pieces of data (68 parameters per engine times two engines per T-38 aircraft times a minimum of three data records per flight).

The increased complexity of the record keeping task, due primarily to RCM/OCM requirements, can be demonstrated by comparing the current engine record level of indenture with the level of indenture which could be required to support RCM/OCM. The current engine record level of indentures are:

All Engines

Type, Model, Series (TMS) Engine

Engine Serial Number (SN)

Major Command Assigned

Base Assigned

By including the RCM/OCM requirement to track components and modules and associating the component with a particular engine SN, the potential level of indenture would be:

All Engines

TMS Engine

Engine SN

MAJCOM

Base

All Components/Modules (C/M)

C/M Used in a TMS Engine

TMS C/M

C/M SN

MAJCOM

Base

Matrix representations of the current and projected records are presented in Figures 14 and 15.

The TEMS data compiled, particularly trended data, at various levels of indenture could be used at each of the management and maintenance levels (see Figure 1) for engine management and maintenance production/engineering purposes. Thus the need for access to and the potential for duplication of TEMS data at base, ALC, and MAJCOM levels can also be projected. Finally, it should be noted from Figure 13 that although the present Engine Status Reporting system may be modified somewhat due to RCM/OCM, TEMS can only supplement it.

ALL ENGINES					
TMS					
SERIAL NO.					
				BASE	MAJCOM

FIGURE 14 - CONCEPTUAL MODEL OF CURRENT ENGINE  
MANAGEMENT RECORD MATRIX

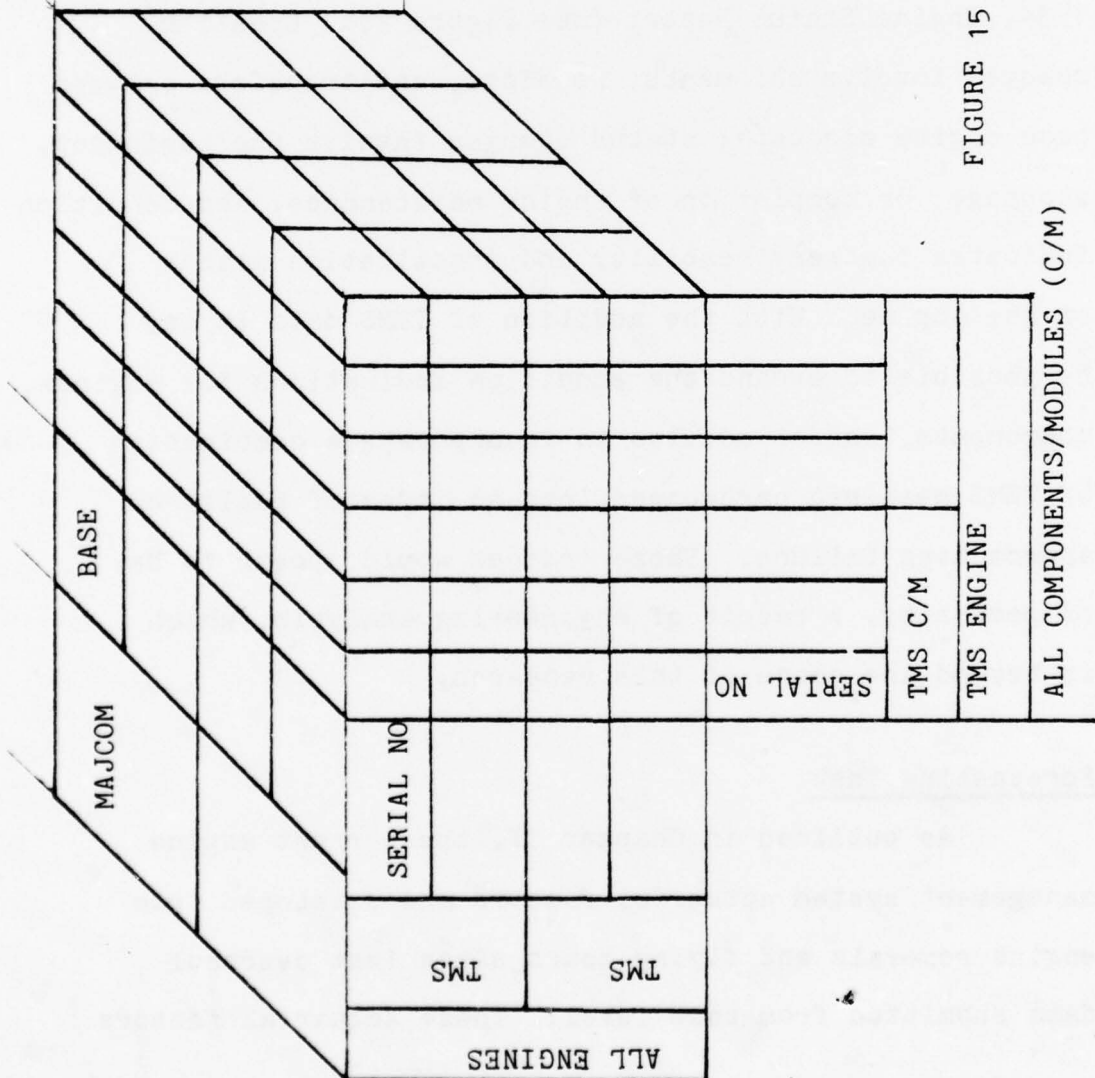


FIGURE 15 - POSSIBLE CEMS  
RECORD MATRIX  
UNDER RCM/OCM

### Monitoring Task

Currently the engine management system accomplishes the monitoring task by producing listings for the EMs and EIMs identifying the location, status, and condition of the engine inventory by TMS or individual engine, base, and/or MAJCOM. These listings are based on engine status change transactions documented via the AF Form 1534, Engine Status Report (see Figure 2). Location changes involve shipments, receipts, and transfers between base engine accounts; status changes involve the beginning, stoppage, or completion of engine maintenance; and condition indicates the serviceability and installation status of the engine. With the addition of TEMS data it may be possible to expand the condition indications for engines, components, and/or modules to incorporate a combination of TEMS measured parameters into an index of health or approaching failure. These indices would appear to be, of necessity, a result of engineering analysis, which is beyond the scope of this research.

### Forecasting Task

As outlined in Chapter II, the current engine management system actuarial factors are developed from engine removals and flying hours since last overhaul data submitted from base level. These actuarial factors

are documented in Engine Failure Rate Tables, such as the example in Figure 16, against which programmed flying hours for any period(s) of interest can be input to produce forecasted failures, workloads, and spares requirements for the period(s). This input-processor-output relationship is shown in Figure 17.

Four factors emerge in interfacing TEMS to this input-processor-output relationship. First, the future program input to forecasting will remain in terms of flying hours. Consequently, forecasts will remain in terms of engine failures and flying hours. Second, RCM/OCM will require the expansion of the record keeping system and modification of the actuarial method or new methods of handling total flying hour input versus the current flying hour since last overhaul input. Third, TEMS performance or engineering data will need to be converted to failure occurrence data to be useful in forecasting. Finally, the current Engine Status Reporting system will continue to be necessary, although modified and expanded, for location and status information. Thus it can be seen, as depicted in Figure 18, that the TEMS interface can only be an addition to the current forecasting system rather than a replacement for existing methods and data.

FLYING HOUR INTERVAL	ENGINE FAILURE RATE	PERCENT SURVIVING AT BEGINNING OF INTERVAL	PERCENT FAILING IN INTERVAL
A	B	C	D
0-20	.0538	100.00%	5.38%
20-40	.0223	94.62	2.11
40-60	.0160	92.51	1.48
60-80	.0124	91.03	1.13
80-100	.0173	89.90	1.56
100-120	.0232	88.34	2.05
120-140	.0249	86.29	2.15
140-160	.0287	84.14	2.41
160-180	.0344	81.73	2.81
180-200	.0431	78.92	3.40
200-220	.0459	75.52	3.47
220-240	.0399	72.05	2.88
240-260	.0364	69.17	2.51
260-280	.0419	66.66	2.80
280-300	.0486	63.86	3.10
300-320	.0532	60.76	3.23
320-340	.0491	57.53	2.83
340-360	.0442	54.70	2.42
360-380	.0444	52.28	2.32
380-400	.0502	49.96	2.51
400-420	.0570	47.45	2.70
420-440	.0682	44.75	3.05
440-460	.0764	41.70	3.19
460-480	.0813	38.51	3.13
480-500	.0845	35.38	2.99
500-520	.0878	32.39	2.85
520-540	.0910	29.54	2.68
540-560	.0940	26.86	2.53
560-580	.0973	24.33	2.37
580-600	1.0000	21.96	21.96
TOTALS		1852.84%	100.00%

FIGURE 16 - EXAMPLE: ENGINE FAILURE RATE TABLE (40:p.6-1)

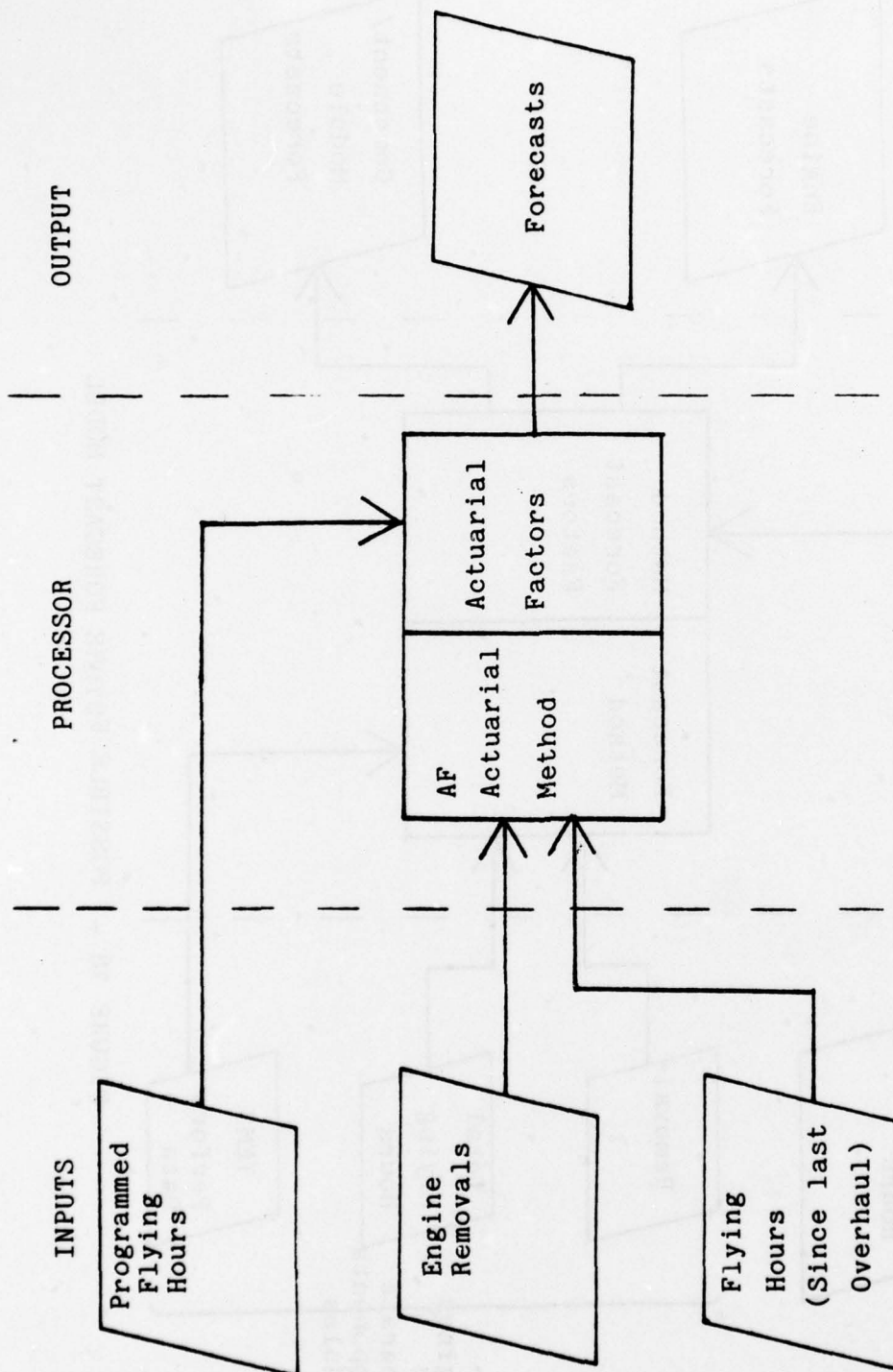


FIGURE 17 - CURRENT FORECASTING MODEL

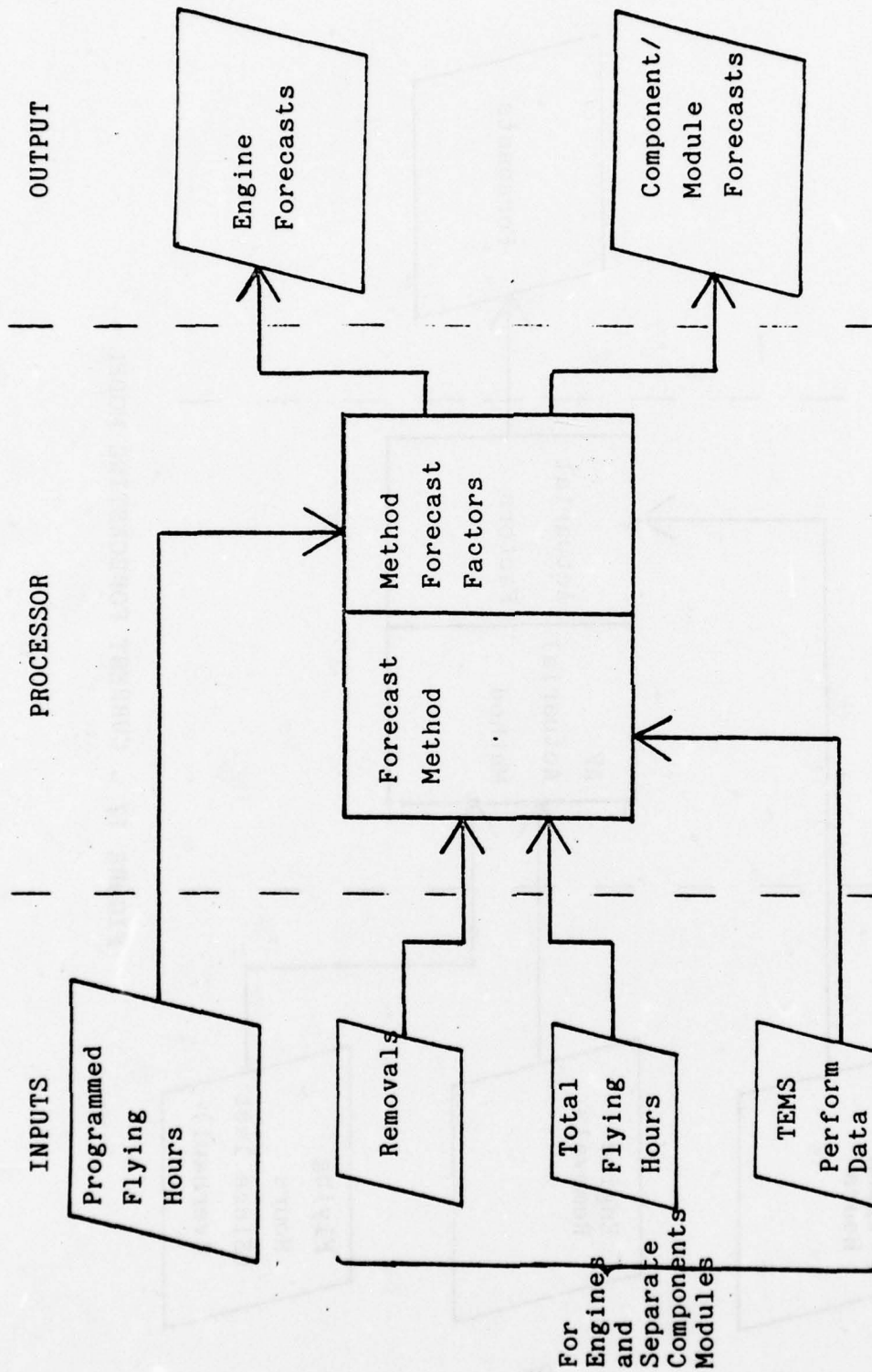


FIGURE 18 - POSSIBLE FUTURE FORECAST MODEL

## CHAPTER V

### CONCLUSIONS AND RECOMMENDATIONS

#### SUMMARY

This study included a comprehensive review of past, current, and proposed Air Force applications of turbine engine monitoring systems. The major features of these systems were analyzed to identify trends in AF TEMS development. Current and proposed AF engine management systems were reviewed to determine the TEMS interfaces with these systems. The research conclusions and recommendations based on the questions identified in Chapter I are presented in the following sections.

#### CONCLUSIONS

##### Research Question One

Research question one:

What are the major features of past, current, and proposed Air Force TEMS applications?

The major features of the systems reviewed were classified according to the conceptual model developed in Chapter III and presented in Figure 6. These classifications are sensors, signal conversion, data processing, and output information. The analysis of service test reports and system

descriptions confirmed that all of the AF TEMS applications reviewed conformed to this system classification.

### Research Question Two

Research question two:

What are the differences and similarities between the reviewed systems, including engine operating parameters monitored and methods of data collection and analysis?

System similarities and differences were analyzed according to the established model. Each of the systems used similar approaches in the sensor and signal conversion segments. The number and types of sensors were consistent and the operating parameters used for engine condition monitoring were similar among the systems reviewed. Some differences were identified in the placement of the signal conversion hardware; however, the conversion process was uniformly applied throughout the systems. Some significant differences existed among the systems in data collection or analysis methodology and presentation of output information. The data collection variations included the use of automatic or manual recording, with automatic recording accomplished by either magnetic tape or electronic data storage. Recorded data was either analyzed in-flight by airborne processing equipment or post-flight by portable TEMS associated ground equipment, data processing support facilities, or manual trend charts. The differences in TEMS output presentation

related to the use of several forms of engine status indicators combined with or independent of the analysis of engine or component faults.

### Research Question Three

Research question three:

Are there any trends in engine monitoring system development in terms of the identified similarities and differences?

Analysis of the reviewed AF TEMS applications in chronological sequence indicated that some trends were apparent within the data processing and output segments of the overall TEMS model. Specifically, TEMS data storage via on-aircraft electronic memory circuits and the use of portable data diagnostic units were more prevalent in the most recent TEMS applications. These techniques appeared to be primarily beneficial to TEMS applications on fighter and attack type aircraft because the weight and volume of on-aircraft TEMS equipment were reduced. Moreover, the portable diagnostic units could be used to obtain the stored TEMS data from several aircraft. The developmental F100 EDS and A-10 TEMS are representative of these trends.

### Research Question Four

Research question four:

How does/can TEMS interface with current and proposed Air Force engine management systems?

The examination of the relationship of TEMS generated output data with the existing engine management system and maintenance concept indicated that the engine performance data from TEMS appears to be more applicable to the maintenance production and engineering tasks than to engine management functions. Moreover, TEMS data is not directly compatible with the current engine status reporting system. The research analysis of the potential impacts of a Reliability Centered Maintenance/On Condition Maintenance concept for AF engines indicated that RCM/OCM would expand the volume and complexity of the data recorded and maintained in the engine management system. This would result from the addition of engine components and modules for condition monitoring to the existing data system as well as documenting the location of these items with their associated engines. The adjustments necessary to the actuarial system resulting from the elimination of the maximum operating time criteria could also affect the complexity of the data system. The implementation of TEMS would also require a similarly complex and voluminous data base to maintain records in the form of performance parameters, detected events, or diagnosed conditions for complete engines, components, and modules.

#### RECOMMENDATIONS

Specific recommendations derived from the analysis of the research questions are:

1. The TEMS interface with CEMS should be accomplished through the maintenance engineering functions by using TEMS output data to verify and/or modify otherwise computed forecasting factors. This should be conducted in conjunction with the existing maintenance engineering tasks. A proposed model of the relationships between engine and maintenance management employing this recommendation is presented in Figure 19. This proposal indicates the flow of TEMS data into the maintenance engineering function and the subsequent interface with the engine management system. The use of TEMS data in the maintenance production function in conjunction with the existing inputs is also indicated in Figure 19.

2. Engine management data and maintenance engineering data from TEMS should be consolidated into a single data base to more effectively implement the RCM/OCM concept. This consolidation could be accomplished through the interface proposed in Figure 19. The central record keeping data base required by the engine management system under the RCM/OCM concept could be expanded to include the addition of a TEMS maintenance engineering data base as depicted by the dotted lines. This would reduce the need to maintain engine records in two parallel systems. Moreover, the expanded availability of both engine failure data from the engine management system and performance data from TEMS could provide the maintenance engineering function a wider variety of data.

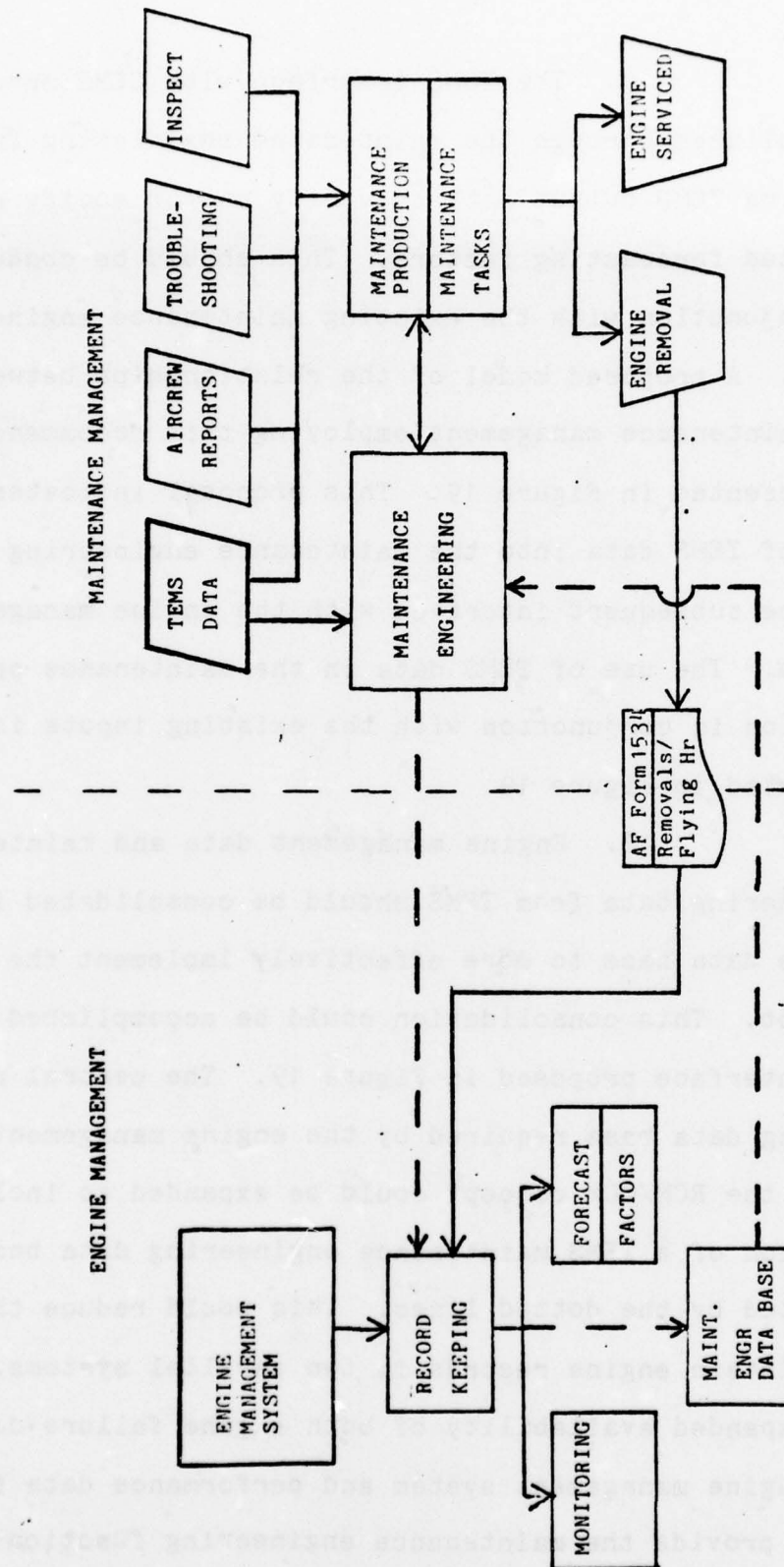


FIGURE 19 - RECOMMENDED TEMS INTERFACE

## RECOMMENDATIONS FOR FURTHER RESEARCH

The impacts of turbine engine monitoring systems on the logistics processes supporting the management of AF aircraft engines were examined in a general context during the course of this study. Two areas were identified for further research regarding specific aspects of the TEMS interface with engine management processes and concepts. These were:

1. Additional research should be conducted to review the use of TEMS generated engine performance data within the maintenance management framework. Specific areas for future analysis include the extent of base level analysis and trending using TEMS output data, which elements of TEMS data are appropriate for use at the base, depot, and command levels of maintenance, and what are the methods which could be employed to interface TEMS data with the existing maintenance data systems. Examination of the results of the current F100 EDS and A-10 TEMS service tests could provide an initial source of information source for this research.

2. As indicated in Chapter IV, the elimination of the maximum operating time removal criteria for engines and some components and modules under the RCM/OCM concept will also eliminate one of the fundamental principles of the actuarial method. Thus, either new methods or modifications to the actuarial system require further research and

development. Moreover, additional research is necessary to determine whether the actuarial factors or factors developed by some new methods can be verified through the use of TEMS data and how this verification could be accomplished.

APPENDIX

## GLOSSARY

Actuarial Engine Life (AEL): This factor is the expected number of flying hours per depot maintenance failure which will occur when the engines are distributed throughout their life span. It is an actuarial factor based on a set of depot maintenance failure rates which vary by age interval from age zero to maximum time. Briefly, it is found by hypothetically flying a group of new engines until ALL have failed, and then dividing the total hours flown by the number of engines (or failures). It is calculated in accordance with definite procedures contained in Section VII of Technical Order 00-25-128.

Actuarial Failure Rate: The measured probability that an engine with age equal to the beginning boundary of an age interval will fail prematurely before aging to the end of that interval.

Actuarial Removal Intervals (ARI): A factor developed for ease in forecasting engine removals. It is a ratio of operating hours to engine removals. An ARI expresses the forecasted average accumulation of engine operating hours by a group of engines, for each engine removal. Generally, a group of engines consists of the entire installed inventory of one type, model, and series (and occasionally more than one series).

Actuarial Science: A mathematical science, the principles of which are applied to human statistics to perform studies in life contingencies, calculate human life expectancy and mortality rates, and compute insurance risks and premiums.

AF Actuarial Method: The method for applying the principles and techniques of actuarial science (especially studies in life contingencies) to the field of Air Force engine management.

AFTO Form 349: Maintenance Data Collection Record.

Base Maintenance: Synonymous with Intermediate Maintenance.

Base Maintenance Removal Interval (BMRI): The ratio of the forecast fleet flying hours per base maintenance removal. The BMRI is computed by dividing the forecast flying hours in a given period of time (usually a 3 month period) by the simulated base maintenance removals for that period. The BMRI is published quarterly for each engine model in the Actuarial Removal Interval Table.

Base Maintenance Return Rate: See Jet Engine Intermediate Maintenance Return Rate, JEBM/RR.

Base Repair Cycle: This phase extends from the removal of a reparable engine until it is ready for reinstallation at the base.

Borescope: A non-destructive inspection process for examination of assembled engines.

CEMS: Comprehensive Engine Management System.

CMRI: Combined Maintenance Removal Interval. A factor developed for use in forecasting total engine removals. The ratio of the forecast flying hours per total usage and max time removals and is published quarterly in the Actuarial Removal Interval Table.

Component: An assembly or any combination of parts, sub-assemblies, and assemblies mounted together in manufacture, assembly, maintenance, or rebuild.

Condition Monitoring: For items that have neither hard time limits nor on condition maintenance as their primary maintenance process. Condition monitoring is accomplished by appropriate means available to an operator for finding and resolving problem areas. These means range from notices of unusual problems to special analysis of unit performance. No specific monitoring system is implied for any given unit.

Cycle: A cycle is basically the start up, stabilization at take off power, flight, landing, and engine shutdown. The temperature excursion involved in heating and cooling constitutes a cycle. The cycle is most significant on rotating parts, wherein the temperature excursion is experienced under centrifugal loading.

Cycle Limit - Component: Life limits that are related to fatigue by repetitions of some usage mode that wears out the component such as revolutions, temperature or pressure excursions, takeoffs, or some combination of these factors.

Dependability Index: A percentage or decimal fraction which is normally derived as the ratio of expected removals to actual removals for a given engine during a given period of time. The reciprocal of the dependability index (the failure index) is used to adjust a set of failure rates for use in forecasting failures during another period of time when changes in engine dependability are expected to occur.

Depot Maintenance Failure: Either a major or minor overhaul performed at depot level. This definition is very important and it should be noted that the word failure is not used here in its usual meaning of in-flight engine failure, but rather to denote a removal for usage reasons. The term "usage" is used interchangeably with the terms "failure for cause" and "premature failure."

Depot Overhaul Cycle: Involves the removal of a reparable engine which is beyond the economic repair capability of the responsible activity and its return to the technology repair center (TRC), as well as its overhaul there, so that it is ready for reissue to the field.

DO24 - Propulsion Unit Logistics System: An engine reporting system that maintains an accurate and timely record of engine inventories, surveillance of base repair, transportation, and overhaul segments of the engine pipeline time, and engine historical data necessary to forecast funding and replacement requirements.

Effective Incipient Failure Detection: That maintenance action which will reliably detect incipient failures if they exist. That is, detect the pending failure of a unit or system before that system fails. For example, detection of turbine blade cracks prior to blade failure.

EHR: Events History Recorder.

Engine Age: The total number of flying hours an engine has accumulated since last major overhaul, or since manufacture if never previously overhauled.

Engine Cycle: A specified operational excursion related to the physical and functional characteristics of a component.

Engine Inventory Manager (EIM): The ALC, or individual at the ALC, responsible for overall logistics management of assigned engines. The term engine inventory manager connotes the functional skills of: (a) Inventory Management Specialist (Requirements and Distribution), (b) Industrial Specialist (Production Management), (c) Equipment Specialist (Technical Services).

Engine Life: Engine life is the number of flying hours which new or newly overhauled engines (age zero hours) attain on an average before being removed for major overhaul for usage reasons or maximum allowable operating time.

Engine Life Span: The overall operating life (in flying hours) of the engine from engine age of zero flying hours up to the maximum allowable operating time. This term should not be confused with the term "engine life."

Engine Manager (EM): The individual responsible for management and reporting of engines at base/command level.

Engine Removal: An engine removed from its mounted position on the aircraft for reasons other than organizational maintenance. For purposes of computation and analysis, the engine removals are separated into the following four types: (a) Field Maintenance, (b) Depot Maintenance, (c) Combined, a combination of both field and depot maintenance, and (d) Condemnation.

Engine Operating Time: The time recorded from start to shutdown in hours and tenths of hours. It includes actual flight time, aborted flight, test cell run, trim run, etc. It is synonymous with Total Operating Time.

ETTR: Engine Time and Temperature Recorder.

Failure: Degraded performance which requires repair before further operation.

Failure Effects: The consequence of failure.

Failure Modes: The ways in which units, systems and aircraft deteriorate and can be considered to have failed.

Failure Rate: A ratio of failed items in an actuarial age interval to the total number of items that began operation in that interval. Failure does not include scheduled removals.

Fault: Degraded performance which does not preclude operation, but is indicative of incipient failure (or reduced failure resistance).

Field Maintenance Failure: An engine removed for field maintenance for usage reasons. Engine age is NOT reset to zero after field maintenance.

Field Maintenance Removal Interval (FMRI): The average number of engine flying hours expected per field maintenance failure during any specified future fiscal year.

Flying Hours: The number of hours that an engine is in the air starting with takeoff to just prior to landing.

Hard Time Limit: A maximum interval for performing maintenance tasks. These intervals usually apply to overhaul, but also apply to total life of parts or units.

Historical Records: Forms that are for maintaining a permanent history of significant maintenance actions for aircraft, drones, missiles, engines and selected modules, assemblies, subassemblies, and/or components.

Inherent Level of Reliability and Safety: That level which is built into the unit and therefore inherent in its design. This is the highest level of reliability and safety that can be expected from a unit, system or aircraft. To achieve higher levels of reliability generally requires modification or redesign.

Installed Engine: An engine installed in an aircraft. An engine removed for any reason will be reported in other than an installed status.

Installed Module: A module installed in an engine. A module removed from an engine for any reason will be reported in other than an installed status.

Intermediate Maintenance: Maintenance that is normally the responsibility of and performed by, designated maintenance activities for direct support of using organizations. Its phases normally consist of calibrating, repairing, or replacing damaged or unserviceable parts, components, or assemblies, modification of material, emergency manufacturing of unavailable parts; and providing technical assistance to using organizations. Intermediate maintenance is normally accomplished by the using commands in fixed or mobile shops.

JEIM: Jet Engine Intermediate Maintenance. Maintenance that is normally the responsibility of and performed by designated field level maintenance organizations.

Jet Engine Intermediate Maintenance Return Rate: The percentage or decimal fraction of engine usage removals, during specified period of time, which are returned to serviceable status through base level maintenance. Also called Base Maintenance Return Rate and Jet Engine Base Maintenance Return Rate.

Life Limited Components: Components or subassemblies of an engine that have absolute time or cycle limits or both. Whenever the first limit is reached, the component must be replaced.

Line Replaceable Unit (LRU): An item that is normally removed and replaced as a single unit to correct a deficiency or malfunction on a weapon or support system and item of equipment. Such items have a distinctive stock number for which spares are locally authorized to support the removal and replacement action. These items may be disassembled into separate components during shop processing. The components are Shop Replaceable Units (SRU).

MADARS: Malfunction Detection Analysis and Recording System.

Maintenance Actions: Those physical tasks that make up maintenance production.

Maintenance Concept: A description of maintenance considerations and constraints submitted as a part of the system acquisition process.

Maintenance Engineering: The application of techniques, engineering skills and effort, organized to ensure that the design and development of weapon systems and equipment provide adequately for their effective and economical maintenance.

Maintenance Plan: The design, method, or scheme for doing a maintenance mission or reaching a maintenance objective.

Maintenance Production: The physical performance of maintenance actions and tasks of the equipment maintenance function.

Maximum Operating Time: The age in operating hours at which an engine will be mandatorily removed for major overhaul.

Maximum Time Removals: Removals due to the expiration of maximum allowable operating time.

MMICS: Maintenance Management Inventory and Control System.

Modular Engine: An engine which is composed of module units. When reporting removal or installation of module units the module engine serial number is considered as the end item.

Module: A module is any major subassembly of an engine that can be separated from an engine as a distinct and separate part thereof and carries a serial number.

Not Mission Capable (NMC): A status code meaning that the system or equipment cannot perform any of its primary missions. It can be followed by a reason code meaning maintenance (M), supply (S), or both (B).

Off-Equipment Maintenance: Maintenance done on components that are removed from end items of equipment for processing through repair shops.

OFR: Official Failure Rate.

On Condition: Repetitive inspections, or tests to determine the condition of units or systems or portions of structure.

On Condition Maintenance (OCM): Maintenance that allows the condition of the equipment to dictate the need for maintenance or the extent of repair/overhaul required.

On Equipment Maintenance: Maintenance performed on end items of equipment, including engines.

Organizational Maintenance: Maintenance that is the responsibility of and performed by a using organization on its assigned equipment. Organizational maintenance normally consists of inspecting, servicing, lubricating, adjusting, and replacing parts, minor assemblies, and subassemblies.

Operating Time: Time recorded for an engine since last major overhaul or since manufactured if never overhauled. On module engines operating time will be reported for the complete engine and the ADP programs will automatically compute the time for the installed modules.

Overhaul: The process of restoring an item to a servicable condition by disassembling the item, inspecting the condition of each of its component parts, and reassembling it using servicable or new assemblies, subassemblies, and parts, followed by inspection and operational tests.

Overhaul Removal Interval (OHRI): OHRI is the ratio of the forecast fleet flying hours per overhaul removal. The OHRI is computed by dividing the programmed flying hours for a specific quarter (based on the HQ USAF Program Auth) by the simulated overhaul removals. The OHRI represents the number of flying hours expected to accumulate on all engines (TMS) before a removal for overhaul is experienced. The OHRI for each engine model is published quarterly in the Actuarial Removal Interval Table. The OHRI may be computed with or without maximum time consideration.

Percent Failing Distribution: The proportion of the total number of engines starting operation at age zero which fail for overhaul within each age interval.

Percent Surviving Distribution: The proportion of the total number of engines starting operation at age zero which survive to the beginning of each age interval based on actuarial overhaul failure rates.

Performance Data: Historical information relating to maintainability, reliability, and supportability characteristics of systems, subsystems, and components.

Queen Bee: A central (selected) base that is authorized or is designated the intermediate maintenance activity for other operational activities not necessarily on the same base or within the same command.

Reduction in Failure Resistance: The deterioration of inherent (design) levels of reliability. As failure resistance reduces, failures increase; resulting in lower reliability. If reduction in failure resistance can be detected, maintenance can be performed prior to the point where reliability is adversely affected.

Reliability: The probability that a system or equipment will perform a required function under specified conditions, without failure for a specified period of time, or at a given point in time.

Reliability Centered Maintenance Program (RCMP): A failure modes and effects analysis technique for significant aircraft and engine structures, assemblies and items. It uses a decision logic procedure based on the Airlines/Manufacturers' Maintenance Planning Document, MSG-2. This structured approach to maintenance requirements analysis, identifies minimum essential requirements consistent with safety and readiness.

Removal Rate: A ratio of removed items to the number of operating items. Removals include both scheduled and unscheduled removals.

Reparable Engine Asset: An aircraft engine determined by proper authority to be in unsuitable operating condition, but which can be made suitable for reuse, and which requires other than organizational or field maintenance.

Routine Flight Crew Monitoring: That monitoring that is inherent in normally operating the aircraft. For example, the pre-flight checklist, or the normal operation of the aircraft and its components. Does not include monitoring of "back-up" equipment that is normally not tested as a part of a normal flight.

SOAP: Spectrometric Oil Analysis Program.

Spare Engine or Module: An uninstalled engine or module not needed to fill an existing hole in an aircraft.

Subsystem: A major functional part of system or end item that is essentially operationally complete within the system.

Subassembly: A unit/item or an assembly consisting of components and/or parts that collectively perform a specific function. These items can be removed, replaced and repaired separately.

System: A final combination of subsystem components, parts, and materials that make an entity capable of doing a specified mission.

TRC: Technology Repair Center (Depot level repair facility).

TO: Technical Order.

TCTO: Time Compliance Technical Order.

TMS: Type, Model, and Series (engine designation).

Usage Failures: Removals due to evidence of engine reliability deficiency associated with use or wear (failure to operate properly); synonymous with "failure for cause" and "premature failure."

**SELECTED BIBLIOGRAPHY**

#### A. REFERENCES CITED

1. Air Force Aero Propulsion Laboratory. "State-of-the-Art Review of Sensors." Letter Report to AFLC/LOP. Wright-Patterson AFB OH, 15 April 1977.
2. Air Force Institute of Technology. Maintenance Management Program: Maintenance Management Information, Volume III. Wright-Patterson AFB OH, March, 1973.
3. \_\_\_\_\_. Maintenance Management Program: Maintenance Management, Volume II. Wright-Patterson AFB OH, April 1979.
4. Air Force Logistics Command, DCS/Logistics Operations. "Comprehensive Engine Management System (CEMS)." Briefing to the Assistant Secretary of the Air Force/Financial Management, Wright-Patterson AFB OH, 22 May 1979.
5. \_\_\_\_\_. "Comprehensive Engine Management System (CEMS)." Briefing to USAF/CC, Pentagon, Washington DC, 14 October 1978.
6. Air Force Logistics Command, Office of the Inspector General. Report of Functional Management Inspection: Engine Conversion to Reliability Centered Maintenance (RCM), PN 79-30. Wright-Patterson AFB OH, 15 May 1979.
7. Air Transport Association of America. Airline/Manufacturer Maintenance Program Planning Document: MSG-2. ATAA, Washington DC, March 1970.
8. Birkler, J.L., and J.R. Nelson. "Aircraft Turbine Engine Monitoring Experience: Implications for the F100 Engine Diagnostic System Program." Unpublished research report No. R-2391-AF, The Rand Corporation, Santa Monica CA, April 1979.
9. Boeing, Roy Lee and Laurence Lee George. "A Work Plan for Enhancement of the Engine and Pipeline Systems: Volume I: Projects." Unpublished technical report, unnumbered, Texas A&M University, College Station TX, October 1977.

10. Brown, J.E., Jr., and others. "Advanced Diagnostic Engine Monitoring System (ADEMS); Design, Fabrication, Flight Test, and Evaluation of ADEMS." Unpublished technical report No. AFAPL-TR-75-24, Air Force Aero Propulsion Laboratory, Wright-Patterson AFB OH, August 1975. AD B005991.
11. Carlson, Major Robert J., USAF. TEMS Program Manager, ASD/YZN, Wright-Patterson AFB OH. Personal interviews conducted intermittently from 31 May to 1 August 1979.
12. \_\_\_\_\_. "TEMS - Purpose, Conclusions, and Recommendations." Presentation to the Sixth Annual Tri-Service Meeting for Aircraft Engine Monitoring and Diagnostics, St. Louis MO, December 1977.
13. Chopin, M.H., and Mark S. Ewing. "Turbine Engine Diagnostic Monitoring Systems: A State-of-the-Art Assessment." Unpublished technical memorandum ENJE-TM-74-10, ASD/ENJ, Wright-Patterson AFB OH, July 1974.
14. Degrande, Major Joe, Jr., USAF, and Major Kenneth E. Eickmann, USAF. "A Study of Turbine Engine Monitoring Systems." Unpublished research report No. 0510-78, Air Command and Staff College, Maxwell AFB AL, 20 April 1978. AD B028596.
15. Dillon, Major William T., USAF. "Diagnostic Data Utilization for Logistics," Presentation to the Sixth Annual Tri-Service Meeting for Aircraft Engine Monitoring and Diagnostics, St. Louis MO, December 1977.
16. Dunham, Marc P. Deputy Director, AFAPL/TBP. Letter, Subject: Low Cycle Fatigue (LCF) in Gas Turbine Engine Discs, to AFLC/MMP, 20 March 1972.
17. Eickmann, Major K.E., and A. B. Richter. "Preliminary Results of USAF Experience with Engine Monitoring and Diagnostics," Proceedings of NATO Advisory Group for Aerospace Research and Development (CP215), The Hague, Netherlands, 1 April 1977.
18. Flynn, John E. "State-of-the-Art Summary: Gas Turbine Engine Monitoring Instrumentation." Unpublished research report No. NAPTC-ATD-153, Naval Air Propulsion Test Center, Trenton NJ, August 1968. AD 844029.

19. Gissendanner, Captain Joel A., USAF. TEMS Project Manager, Propulsion Systems Division, San Antonio ALC, Kelly AFB TX. Telephone interviews conducted intermittently from 3 November 1978 to 16 January 1979.
20. \_\_\_\_\_. "An Assessment of the T-38 Engine Health Monitoring System (EHMS) Service Evaluation." Unpublished report, unnumbered, SA-ALC/MMP, Kelly AFB TX, June 1978.
21. Harris, W. J. "Turbojet Engine Analyzer System." Unpublished technical report No. SEG-TR-67-44, Aeronautical Systems Division (AFSC), Wright-Patterson AFB OH, June 1969.
22. Hayes, Major General William R., Director of Maintenance, Engineering, and Supply, HQ USAF/LGY. Letter, subject: Maintenance Posture Improvement Program, to AFLC/MM, 25 September 1974.
23. Kohlberg, Major Bernard J., Jr., USAF. Director, On Condition Maintenance, Directorate of Propulsion Systems, HQ AFLC, Wright-Patterson AFB OH. Personal interviews conducted intermittently 30 May through 1 August 1979.
24. McDonnell Aircraft Company. F100 Engine Diagnostic System Hardware and Software Definition Phase. MDC A4270, St Louis MO, 15 July 1976.
25. Neumann, Curtis E., and Michael W. Simmons. "Engine Diagnostic Effectiveness and Trending." Unpublished research report No. 76-3-2, AFLC/XRS, Wright-Patterson AFB OH, September 1977.
26. Northrop Corporation Electronics Division. Description of the Northrop Engine Health Monitor System. NORT 76-206, Palos Verdes Peninsula CA, February 1976.
27. \_\_\_\_\_. T-38 Engine Health Monitoring System (EHMS): Hardware Demonstration Program Final Report. NORT 73-266, Palos Verdes Peninsula CA, June 1973.
28. Oklahoma City Air Logistics Center, CEMS Development Project Office. Comprehensive Engine Management System: CEMS Functional Description, Section I, Tinker AFB OK, December 1978.

29. Pettigrew, Lt Col James L. "Engine In-Flight Monitoring Update," Combat Crew, July 1977, pp. 10-12.
30. \_\_\_\_\_. "Propulsion Reliability Improvement Through Inflight Monitoring Performance Monitoring," Combat Crew, January 1977, pp. 9-11.
31. Rutley, Captain William D., USAF. Director of On-Condition Maintenance, Directorate of Propulsion Systems, HQ AFLC, Wright-Patterson AFB OH. Personal interviews conducted intermittently from 26 October 1978 to 15 January 1979.
32. San Antonio Air Logistics Center, Propulsion Management Division. "A-10/TF34 Turbine Engine Monitoring System (TEMS) Service Evaluation Plan." Unpublished technical report, unnumbered, Kelly AFB TX, August 1978.
33. Schotta, E.A., and R. Rosenbrock. "An Assessment of IECMS Cost-Benefit." Unpublished technical report No. 200-76-01, Naval Aviation Integrated Logistics Support Center, NAS Patuxent River MD, 15 February 1976.
34. Technical Cooperation Program, Aeronautics Subgroup. Outlines of Current Military Gas Turbine Engine Health Monitoring Programs. TTCP technical report HAG-2-76, September 1976.
35. TEMS Review Group. "Logistics Committee Report," Scott AFB IL, 16-17 February 1977.
36. \_\_\_\_\_. "Turbine Engine Monitoring System (TEMS) Review Group Report." Briefing presented to AFLC/LO, Wright-Patterson AFB OH, 25 May 1977.
37. Williams, Dr. Benjamin R. Program Director, Comprehensive Engine Management System (CEMS), DCS/Logistics Operations, HQ AFLC Wright-Patterson AFB OH. Personal interviews conducted intermittently from 1 November 1978 to 1 August 1979.
38. U.S. Department of Defense. DOD Planning and Programming Guidance Memorandum (PPGM FY 77-82). Washington: Government Printing Office, 1976.

39. U.S. Department of the Air Force. Equipment Maintenance Policies, Objectives, and Responsibilities. AFR 66-14. Washington: Government Printing Office, November 1978.
40. U.S. Department of the Air Force. Procedures for Determining Aircraft Engine (Propulsion Unit) Failure Rates, Actuarial Engine Life, and Forecasting Monthly Engine Changes by the Actuarial Method. Technical Order 00-25-128. Washington: Government Printing Office, November 1965.
41. U.S. Department of the Air Force. Selective Management of Propulsion Units: Actuarial System for Engines. AFM 400-1, Volume III. Washington: Government Printing Office, April 1969.
42. U.S. Department of the Air Force. Selective Management of Propulsion Units: Engine Status Reporting. AFM 400-1, Volume II. Washington: Government Printing Office, August 1975.
43. U.S. Department of the Air Force. Selective Management of Propulsion Units: Policy and Guidance. AFM 400-1, Volume I. Washington: Government Printing Office, June 1976.
44. U.S. Department of the Air Force. USAF Program Guidance (PG-78-3). Washington: Government Printing Office, 7 May 1976.
45. Zerkle, Hollis G. "Development and Test of the Engine Analyzer System." Unpublished research report, unnumbered, Aeronautical Systems Division, Wright-Patterson AFB OH, August 1967. AD 665158.

#### B. RELATED SOURCES

- Air Force Logistics Command. Concept Certification Documentation for the Comprehensive Management System (CEMS). Wright-Patterson AFB OH, 1 January 1979.
- Air Force Logistics Command, DCS/Logistics Operations. "On Condition Maintenance Policy Considerations." Position paper, AFLC/LOP, Wright-Patterson AFB OH, 30 June 1977.
- \_\_\_\_\_. "Engine Fiscal Year Cost Analysis." Staff Study, AFLC/LOP, Wright-Patterson AFB OH, 1977.

- Air Force Systems Command, Aeronautical Systems Division.  
"F100 Engine Diagnostic System." Briefing to AFLC/CC,  
TAC/CV, AFSC/CV, and USAF/RD/LG, Pentagon, Washington  
DC, November 1976.
- Brady, Captain James F., USAF, and Captain Michael J.  
Scratchfield, USAF. "An Examination of the Current  
United States Air Force Engine Reporting System."  
Unpublished master's thesis. SLSR 9-72B, AFIT/SL,  
Wright-Patterson AFB OH, September 1976. AD 750910.
- Carlson, Major Robert J., USAF, and Richard J. Smith.  
"The Engine Actuarial System." Unpublished master's  
thesis. SLSR 7-76A, AFIT/SL, Wright-Patterson AFB  
OH, June 1976. AD A030312.
- Flynn, John E. "Requirements for Advancement of Technology:  
Gas Turbine Engine Monitoring Instrumentation." Unpublished  
research report No. NAPTC-ATD-163, Naval Air Propulsion  
Test Center, Trenton NJ, October 1968. AD 846179.
- Meador, B.M., and J.F. Nemecek. "Advance Airborne System  
for Maintenance Monitoring." Presentation to the  
Society of Automotive Engineers Committee for Aircraft  
Gas Turbine Engine Monitoring, San Antonio TX, 24  
February 1977.
- Nelson, J.R. "Life Cycle Analysis of Aircraft Turbine  
Engines: Executive Summary." Unpublished research  
report No. 2103/1-AF, The Rand Corporation, Santa  
Monica CA, March 1977. AD A039062.
- Northrop Corporation Electronics Division. "A-10/TF34  
Engine, Health Monitor System (EHMS) USAF Program  
and Flight Installation Review." Briefing; Myrtle  
Beach AFB SC, 9 May 1978.
- Pobanz, SMSgt Kenneth W., USAF. HQ TAC Propulsion/TEMS  
Monitor, TAC/LGMS. Langley AFB VA. Personal and  
telephone interviews conducted intermittently from  
17 January to 18 April 1979.
- Sallee, G.P. "Technical Evaluation Report on Power  
Plant Reliability; AGARD Advisory Report No. 110,"  
Advisory Group for Aerospace Research and Development,  
The Hague, Netherlands, November 1977. AD A048081.
- Skovholt, R., and others. "Integrated Engine Instrument  
System Final Technical Report - Volume II." Unpublished  
technical report No. 76180-30, Naval Air Development  
Center, Wilmington MA, June 1976. AD A35566.

Urban, L.A. "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines," Journal of Engineering for Power, April 1975, pp. 225-230.

U.S. Department of the Air Force. Maximum Operating Hours for Removal of Aircraft Engines, Modules, and Gearboxes, and Use of Engines Removed from Phased Out of Inventory Aircraft. Technical Order 2-1-18. Washington: GOVERNMENT PRINTING OFFICE, March 1978.

Vogel, A.R. Chief, Diagnostic and Safety Systems, Northrop Corporation Electronics Division, Palos Verdes Peninsula CA. Personal interview, 22 February 1979.